

Characterisation of *Eucalyptus nitens* plantations for veneer production

by

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Declarations

This thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information and duly acknowledged in the thesis, and to the best of my knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the thesis, nor does the thesis contain any material that infringes copyright.

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27/05/2016

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Statement of co-authorship

The following statement identifies people who contributed to the publication of Chapter 2 and Chapter 3 undertaken as part of this thesis.

Chapter 2 has been slightly modified from an original research article which has been published for publication in the peer-reviewed journal *Annals of Forest Science*. This chapter was published as:

Vega M, Hamilton M, Blackburn D, McGavin R, Baillères H, Potts B (2015) Influence of site, storage and steaming on *Eucalyptus nitens* log-end splitting. *Annals of Forest Science* (DOI 10.1007/s13595-015-0496-3).

The candidate, Mario Vega, wrote the first draft of the manuscript, assisted by supervisors Matthew Hamilton and Brad Potts, and other co-authors subsequent assisted with edits. Mario Vega led the data collection, and all other co-authors contributed to data collection except Brad Potts. David Blackburn and Matthew Hamilton were responsible for log selection and supply logistics. Mario Vega, with advice from Matthew Hamilton and Brad Potts, undertook statistical analyses. Robert McGavin and Henri Baillères were actively involved in the design of the experiment and oversaw the processing of logs.

Chapter 3 was partially published as a poster:

Vega, M; Hamilton, M; Downes, G; Harwood, C; Adams, P; Potts, B (2013) Near infrared calibrations to predict modulus of elasticity for plantation grown *Eucalyptus nitens*. 18th International Nondestructive Testing and Evaluation of Wood Symposium. USDA, Forest Service, Forest Products Laboratory. September 24-27, 2013 Madison, Wisconsin, USA.

Mario Vega wrote the first draft of the manuscript, assisted by Matthew Hamilton, Brad Potts and Chris Hardwood. All authors undertook editing of the manuscript. Mario Vega with advice particularly from Matthew Hamilton and Geoffrey Downes undertook statistical analyses.

The following statement identifies people who contributed to the three publications in the Appendix which resulted from activities undertaken as part of a larger project the candidate was involved with.

Hamilton M, Blackburn D, McGavin R, Baillères H, Vega M, Potts B (2014) affecting log traits and green rotary-peeled veneer recovery from temperate eucalypt plantations. *Annals of Forest Science* 72, 357-365.

Matthew Hamilton oversaw the selection, felling and transport of logs, undertook statistical analyses and wrote the first draft of the manuscript. The candidate along with the other co-authors contributed to draft revisions and editing. The candidate was involved in field work (project design, tree and plot selection, felling and log preparation) and pre- and post-peeling data assessments. The specific data collected for this paper was undertaken by the candidate along with David Blackburn and Matthew Hamilton working as a team. Robert McGavin and Henri Baillères oversaw the peeling of logs.

McGavin R, Baillères H, Lane F, Blackburn D, Vega M, Ozarska B (2014b) Veneer recovery analysis of plantation eucalypt species using spindleless lathe technology. *Bioresources* 9, 613-627

McGavin R, Baillères H, Hamilton M, Blackburn D, Vega M, Ozarska B (2014a) Variation in rotary veneer recovery from Australian plantation *Eucalyptus globulus* and *Eucalyptus nitens*. *Bioresources* 10, 313-329.

The last two papers are based on assessments of veneer from the peeled logs derived from the experiment candidate was involved in as part of a research team. His contribution in providing the logs for this peeling study, included involvement in project design, tree and plot selection, felling and log preparation and pre- and post-peeling data assessments (including veneer grading). Robert McGavin and Henri Baillères oversaw the peeling of logs. McGavin and Baillères undertook statistical analyses and wrote the first draft of the manuscripts. All authors undertook revision/editing of the manuscripts.

We the undersigned agree with the above stated "proportion of work undertaken" for each of the above published (or submitted) peer-reviewed manuscripts contributing to this thesis:

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Abstract

Eucalyptus nitens is widely planted in temperate-cold regions around the world, mainly for pulpwood production. However there is interest in its use for veneer-based engineered wood products to increase the value and market opportunities for the *E. nitens* plantation resource. This study examined such opportunities by studying factors which affect veneer recovery as well as those which influence wood properties important for veneer quality.

This thesis had four main experiments. The first experiment examined log-end splitting with respect to log storage, steaming, plantation site and tree position. Log-end splitting is a major defect of *Eucalyptus* logs which has the potential to significantly reduce the recovery of veneer. Log-end splitting was assessed immediately post-felling, after transport and storage and immediately prior to veneer peeling, using upper and lower logs from each of 41 trees from three 20-22 year old plantations. The study found that log-end splitting varied across sites, was higher in upper than lower logs, and increased with time in storage particularly in the upper log. In the system studied, log steaming did not significantly affect the severity of log-end splitting.

The three remaining studies dealt with the assessment of three important wood properties: density, microfibril angle and modulus of elasticity. SilviScan was the main approach used for assessing radial and site variation in these characteristics. However, in the second study an attempt was made to develop more rapid and cost effective approaches using near-infrared spectroscopy. Radial scans of breast-height samples from 86 trees and three sites were used to successfully develop near-infrared calibrations of these wood properties against 1 mm resolution SilviScan measurements. However, the capacity of these models to predict wood properties when applied to independent sites was mixed and generally poor. SilviScan measurements were therefore used throughout the remainder of the thesis where comparisons across sites were the main focus.

The third study examined radial change in density, microfibril angle and modulus of elasticity. While radial change in these veneer-critical wood properties is known to occur, the extent to which patterns vary, both between sites and trees within sites, is poorly understood in *Eucalyptus*. Radial models were developed to determine the trends in these wood properties from pith to cambium using samples from 2.5 m above ground level taken from forty-one 20-22 year old trees from three *E. nitens* plantations. Simple linear regression models were used to model density, while non-linear functions were used to model the radial variation of microfibril angle (asymptotic function) and modulus of elasticity (sigmoidal function), against both cambial age and percentage area from pith. The radial trends from pith to cambium in density, microfibril angle and modulus of elasticity found in this study were clear and matched the general trends in other studies of *Eucalyptus*. However, significant differences were obtained in the pattern of radial variation in these wood properties both among trees within sites as well as between sites. The radial patterns of change were similar regardless of whether they were assessed based on cambial age or percentage of the cross-sectional area and site rankings were the same.

Lastly, the site variation in density, microfibril angle and modulus of elasticity across the Tasmanian *E. nitens* plantation estate was modelled. This study was based on area-weighted tree means obtained from radial SilviScan data. Three trees from each of 46 sites were used to develop the models and those from an additional 13 sites used as a validation data set. Site-level averages for the three wood properties were modelled using various forest, environmental and climatic variables as explanatory variables. Stepwise backward regression was used to select the most parsimonious linear model for each wood property. The final models included only plantation age and annual precipitation for all three wood properties as well as elevation for density. These models were well validated and used to map predicted spatial variation in these veneer-critical wood properties across the Tasmanian plantation estate to aid resource characterisation and forest management.

A key result to emerge from this thesis was the importance of site-level factors on log traits and wood properties likely to impact the quantity and quality of veneer

from Tasmanian *E. nitens* plantations. This thesis was able to characterise and predict variation in these wood properties, both within individual trees and across the Tasmanian plantation estate. These results have direct management implications, allowing quantification of the impact of different growing conditions on the wood properties of harvested logs and therefore on the potential veneer recovery. Coupled with growth and economic models, these results will assist in optimisation of available forestry resources and future planning.

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Chapter 1 Introduction

1.1 Global forest plantation resources and the role of Eucalyptus species

The increasing global importance of forest plantations in supplying the wood processing industry, particularly with round wood, has become increasingly evident in recent decades (Payn *et al.* 2015). Although the worldwide forest plantation estate is about 277.9 million hectares, representing only 7% of the total global forest area, plantations supplied 46.3% of industrial round wood (excluding fuel wood) in 2012 (Payn *et al.* 2015). *Eucalyptus* plantations comprise 19.6 million hectares worldwide and thus represent 7.4% of worldwide plantation area (FAO 2006). Of these eucalypt plantations, 35% are located in temperate and Mediterranean zones and *Eucalyptus nitens* is one the most common species planted in these zones (Forrester *et al.* 2010).

E. nitens is the second most prevalent hardwood plantation species in Australia and the most abundant in the southern island state of Tasmania (Forestry Tasmania 2011; Gavran 2013). Approximately 208,000 ha of this species have been planted representing 88.4% of hardwood plantations in Tasmania (Gavran and Parsons 2011). Although the majority of hardwood plantations in Tasmania are managed to supply pulpwood, since the early 1990s 15% of *E. nitens* plantations have been pruned and thinned with the aim of producing high-value sawlogs (Forestry Tasmania 2011; Gavran 2013; Gavran and Parsons 2011).

The *E. nitens* plantations will supply Tasmania's forest processing industries, which have traditionally used logs from mature and re-growth native forests. However, plantation-grown eucalypts have not previously been processed on a large scale in the state. Several studies on *E. nitens* have examined the potential for industrial processing, mainly for sawn timber (Blackburn 2012; Blackburn *et al.* 2010; Harwood 2010; Valencia *et al.* 2011; Washusen 2011; Washusen and Harwood

2011; Wood M 2011). The veneer potential of *E. nitens* has been less intensively studied (Blackburn *et al.* 2012; Blackburn and Nolan 2014; Blakemore *et al.* 2010), however, preliminary research indicates that it has the potential to yield higher economic returns than sawn wood (Blakemore *et al.* 2010; Farrell *et al.* 2011).

In addition, veneer processing may be more suitable for species, such as *E. nitens*, which have a tendency to split and crack during the sawing and drying process, thus reducing the value of more traditional solid wood products such as sawn timber (Blakemore *et al.* 2010; McGavin *et al.* 2014b).

Rotary-peeled veneer is produced using lathes that peel a continuous layer of wood from rotating logs (Baldwin 1995b and Figure 1.1). Such veneers are the basic element used in the manufacture of engineered wood products such as plywood, and laminated veneer lumber (LVL). Their quality is assessed using both visual and mechanical criteria, visual assessment focuses mainly on external features such as the size and distribution of knots, while mechanical assessments are based on wood properties, principally modulus of elasticity (Australian/New Zealand Standard 2012).

Producing appearance-grade veneer from fast-grown *E. nitens* plantation wood is challenging, particularly given the cost of thinning and pruning plantations for this purpose (Blakemore *et al.* 2010). Structural-grade veneer represents an alternative to pulpwood and appearance-grade veneer as a market for the Tasmanian *E. nitens* plantation resource (Blackburn and Nolan 2014). The industry requirements for structural-grade veneer are discussed in the following section.



Figure 1.1 a) Diagram of rotary-peeled veneer produced using a lathe. Figure modified from García *et al.* (2002). b) Example of continuous ribbon of veneer peeled from *E. nitens* logs (from this project).

1.2 *Industrial wood quality requirements for veneer*

The veneer industry demands specific characteristics of its raw materials. Firstly, rotary veneer processing require logs with uniform shape, characterised by minimal sweep and taper (Baldwin 1995b), which is the case for *E. nitens* plantation trees (Hamilton *et al.* 2014; Medhurst *et al.* 2012; Potts *et al.* 2011). Internal characteristics are also crucial in the production of structural grade products (Lutz 1978), including wood properties such as density, shrinkage and stiffness. Accordingly, mechanical properties such as density and modulus of elasticity are commonly assessed in the processing industry. Microfibril angle (MFA) is not commonly assessed but is strongly associated with shrinkage, modulus of elasticity, dimensional stability and other wood properties of interest.

Density

Wood density is the most common property used to characterise wood quality because it is closely related to the mechanical and physical properties of wood (Shmulsky and Jones 2011b). Density is defined as weight per unit of volume, usually expressed as kilograms per cubic meter (kg m^{-3}). Density is commonly measured as oven dry weight per unit of green volume, which is denoted as ‘basic density’. Green and air-dried density may also be used, which use green or air-dried weight respectively in the calculation of density (Shmulsky and Jones 2011a).

Density is positively correlated with stiffness (Forest Products Laboratory 2010) and so higher values would be expected to produce veneer of higher structural grade. However, in the production of veneer-based engineered wood products, species with high density wood can cause problems in the peeling and glueing processes. Notable examples of species which experience such issues include *Tectona grandis* and *Dalbergia nigra* (Frihart and Hunt 2010). *E. nitens* is characterised by moderate wood density. Basic density in the species has been reported as 478 kg m^{-3} at 14 years (Blackburn 2012) and 488 kg m^{-3} at 20 years (McKimm *et al.* 1988) from breast-height sampling. As

such it might be expected that *E. nitens* would exhibit less of these problems than species with higher density.

Microfibril Angle (MFA)

Microfibril angle (MFA) is defined as the angle between the direction of crystalline cellulose fibrils in the cell wall and the longitudinal direction of the cell (Barnett and Bonham 2004), depicted in Figure 1.2. It is well recognised that MFA of the woody cell wall S_2 layer has a critical influence on the behaviour of wood, especially, in its mechanical and physical properties (Barnett and Bonham 2004; Butterfield and Meylan 1980; Evans and Ilic 2001; Walker and Butterfield 1996). High values of MFA have an adverse effect on stiffness, strength and shrinkage (Barnett and Bonham 2004) and so lower values of MFA are better for structural grade veneer products.

In general for conifers and hardwoods, values of MFA are large in corewood and small in the outerwood (Forrester *et al.* 2013; Medhurst *et al.* 2012). In the case of conifers this change reflects a difference between juvenile and mature wood (Zobel and Buijtenen 1989a). Hardwoods, however, generally show less radial variation and have a lower MFA in corewood wood than conifers (Donaldson 2008). In the case of *Eucalyptus spp.* there is not an accepted definition of juvenile wood with respect to age or distance from the pith (Kojima *et al.* 2009). In case of 15 year old *E. nitens* trees reported values of MFA close to the pith are 19 degrees but this decreases to 12.5 degrees in wood near the cambium (Evans *et al.* 2000).

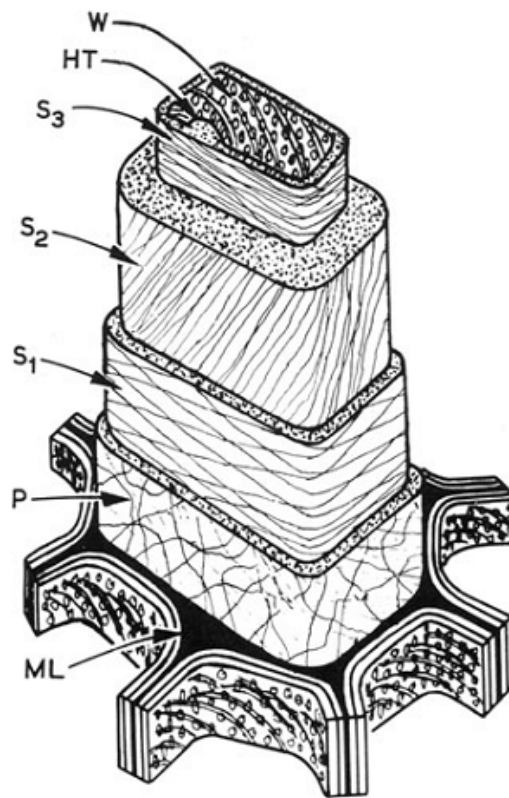


Figure 1.2 A schematic diagram to illustrate the general structure of the cell wall of axially elongated wood elements and the dominant, helical orientation of the cellulose micro fibrils within each wall layer. ML, middle lamella; P, primary wall, S1, outer layer of the secondary wall, S2, middle layer of the secondary wall; S3, innermost layer of the secondary wall; HT, helical thickening; W, warty layer. Microfibril angle is the angle between the direction of crystalline cellulose fibrils in the S2 cell wall and the longitudinal direction of the cell (Butterfield and Meylan 1980)

Modulus of Elasticity (MOE)

The resistance to deformation under load (referred as to stiffness), is one of the most important mechanical properties and is crucial for wood products used in structural applications (Shmulsky and Jones 2011b). Timber stiffness indicates the deflection of a board under load and is measured by static modulus of elasticity, which is calculated from the linear portion of the load deflection curve (Raymond *et al.* 2007), as shown in Figure 1.3. Reported static modulus of elasticity values from *E. nitens* plantations range from 8.6 to 13.9 GPa at 12% moisture content (Farrell and Mihalcheon 2010).

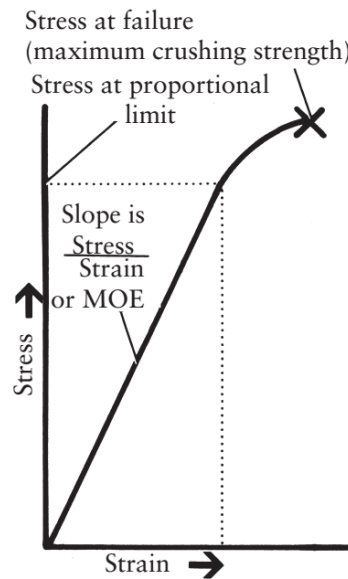


Figure 1.3 Relation between stress and strain (modulus of elasticity) in a typical compression parallel-to-grain bending test (Shmulsky and Jones 2011b).

For veneer-based engineered wood products, stiffness is used to determine the stress grade of the product (Australian/New Zealand Standard 2012). Stiffness of veneer itself can be measured using the longitudinal stress wave method, that is referred to as dynamic modulus of elasticity (MOE_d) to distinguish it from the static modulus of elasticity from bending tests (Raymond *et al.* 2007). The longitudinal method used relies on measuring the velocity of stress waves along the grain of a known length of timber, using the equation below to calculate dynamic modulus of elasticity (MOE_d) in gigapascals (GPa):

$$MOE_d = density * velocity^2$$

where density is the air-dried density of the sample, in this case the veneer (Raymond *et al.* 2007).

Static modulus of elasticity is strongly correlated with MOE_d (Ilic 2001), although values of MOE_d can be around 10% higher than static modulus of elasticity (Harwood *et al.* 2005b; Ilic 2001; Raymond *et al.* 2007). Blackburn (2012) reported a mean MOE_d for veneers produced from 15 year old *E. nitens* of 11.6 GPa, while higher values were reported by McGavin *et al.* (2015) with 14.5 GPa for trees of 20 and 22 years old.

Static and dynamic modulus of elasticity also exhibit radial variation but with the opposite trend to MFA. Wood close to pith has lower static modulus of elasticity than wood near to cambium in both conifers and hardwoods (Zobel and Sprague 1998). In *E. nitens*, McGavin *et al.* (2015) reported values of dynamic MOE_d of 10.6 and 15.7 GPa for veneer wood close to the pith and bark, respectively.

1.3 Optimising the veneer potential of *E. nitens* plantations

As discussed above, the required value of wood properties varies according to the end product in question. As wood properties vary within and among individual trees, stands and forests, any given forest resource can be used to develop a range of end products (Chauhan *et al.* 2006a; Moore and Cown 2015a). The potential of a forest resource for veneer products therefore depends on a number of factors, including:

- market forces which determine the demand for, and value of, different end products;
- the feasibility, cost and efficiency of processing; and
- the availability of forest resources with suitable wood properties.

Within the forestry and wood processing industry, therefore, the economic viability of veneer processing can be optimised in two main ways: firstly, by increasing the efficiency of production processes and end product recovery from available resources; and secondly by optimising the use of the forest resource itself by better matching the resource to targeted products.

The application of these two options to the Tasmanian *E. nitens* plantation resource forms the conceptual framework for the exploration of opportunities for improving the use of the *E. nitens* resource. Concepts surrounding these options are introduced in the following sections.

1.3.1 Improving recovery

Maximising the recovery of veneer per unit of stem volume is generally recognised as an important objective when maintaining or enhancing productivity (Malan

2003). This can be achieved in many different ways, for example by reducing wastage during tree harvest, optimising storage conditions, applying treatments to the logs before and during processing, and by increasing the efficiency of the manufacturing processes themselves.

Typically, in the production of veneer products, harvested logs are stored, often under sprinklers to avoid dehydration, prior to processing and a heat treatment is commonly applied. The logs are then peeled while still green. The quality of the veneer sheets obtained may be assessed while the wood is green, and/or once the wood has been dried.

This thesis and associated studies focused on potential opportunities for optimising yield from *E. nitens* logs by improving:

- storage and log steaming practices;
- peeling technology;
- veneer green recovery; and
- veneer dry recovery.

The first stage, storage and log steaming (depicted in Figure 1.4), is the focus of Chapter 2 of this thesis. Peeling technology and veneer recovery also (shown in Figure 1.5) were examined during this project and are discussed briefly below. However, as they were collaborative studies in which the author of this thesis is a co-author but not the main author, they are not included as chapters in the thesis.

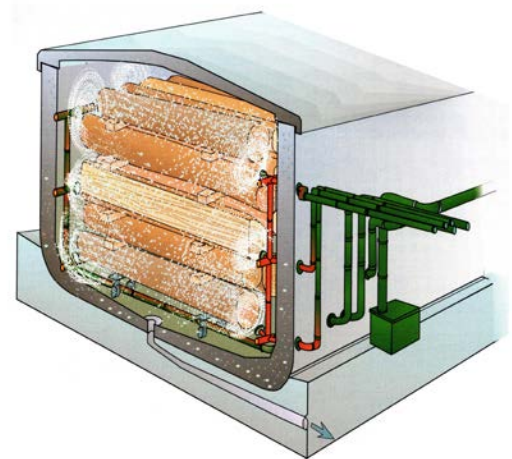


Figure 1.4 Log steamer (García *et al.* 2002)

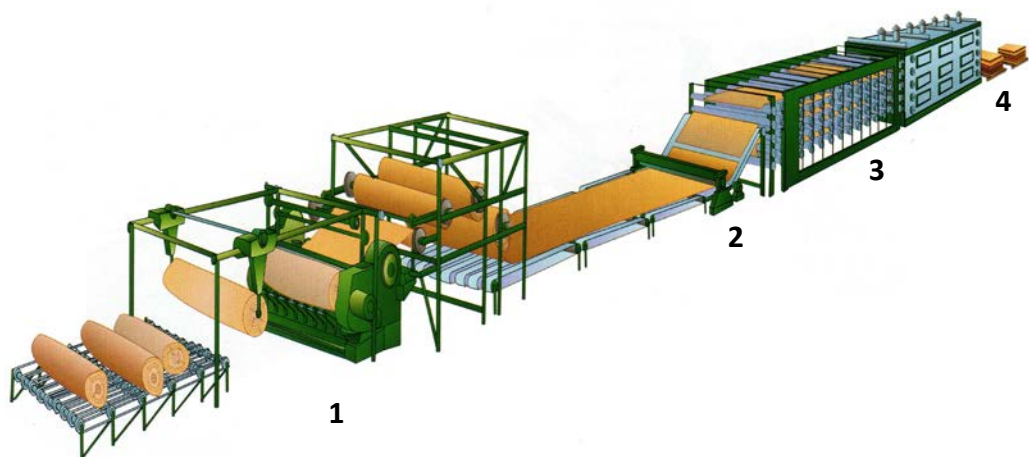


Figure 1.5 A schematic diagram to illustrate the peeling process, modified from García *et al.* (2002). 1- Lathe. 2 - Green recovery. 3 - Dryer. 4 - Dry veneer recovery.

Storage and log steaming: the influence of site, storage and steaming on E. nitens log-end splitting

Log- end splitting, where logs develop cracks and splits from the cut surfaces, is recognised as a major problem in eucalypt logs, and as one of the single most important defects in veneer logs as it can substantially reduce the recovery of veneer sheets (Kromhout and Bosman 1982). Vega *et al.* (2015) and Chapter 2 show that this phenomenon varies across sites and within-tree log position and increases with time in storage, but in the system studied there was no detectable effect of the application of a pre-peeling steam treatment, contrary to previous reports.

Peeling technology: Veneer recovery analysis of plantation eucalypt species using spindleless lathe technology

In a study undertaken in parallel to this thesis, McGavin *et al.* (2014b) investigated the effectiveness of the use of spindleless lathe technology on Australian hardwood species, including *E. nitens*. The spindleless lathe is a relatively new technology which was developed for the processing of small-diameter logs, and, as such, is very relevant for fast-growing plantation hardwoods, such as *E. nitens*. The study demonstrated that spindleless lathe technology is an effective processing method for plantation hardwood trees, including *E. nitens*. The recovery rates were in the order of two to six times the rates achieved using more traditional solid wood

processing techniques and produced veneers suitable for the manufacture of structural products (McGavin *et al.* 2014b).

Green recovery: Factors affecting log traits and green rotary-peeled veneer recovery from temperate eucalypt plantations

In a second study undertaken in parallel to this thesis, Hamilton *et al.* (2014) indicated that temperate eucalypt plantations produce high recovery rates of green veneer, although these rates were affected by site and log position in the stem. Green recovery was measured as the yield of veneer sheets immediately post peeling as a proportion of the original log volume. Of the log traits measured immediately post-felling, out-of-roundness (measured as the difference between the minimum and maximum diameter divided by the average of the minimum and maximum diameter) was the best predictor of the green veneer recovery

Dried veneer recovery by grade in E. nitens: Variation in rotary veneer recovery from Australian plantation Eucalyptus globulus and Eucalyptus nitens.

McGavin *et al.* (2014a) extended the results of Hamilton *et al.* (2014) by investigating the recovery variation of the same green veneer after drying in an industrial dryer. Sites that were thinned and pruned exhibited much better dried veneer recovery with respect to gross, net, and grade recoveries, in comparison to the site that was not thinned or pruned. The best-performing site achieved a 45% recovery of C-grade or better veneers. This exceeds the minimum grade quality proportions nominated by the Engineered Wood Products Association of Australasia (30% to 40%) necessary for the commercial production of structural panel products.

All four of these studies indicate that veneer processing is highly applicable to the *E. nitens* resource, with high green and dried recovery rates of structural grade veneers from available harvested *E. nitens*, albeit with veneer recoveries dominated by lower grades (Hamilton *et al.* 2014; McGavin *et al.* 2014a; McGavin *et al.* 2014b). The strong site effects shown on log-splitting and rates of veneer recovery suggests, however, that a greater understanding and subsequent management of the drivers

influencing variation of wood properties within forestry resources could also substantially improve veneer recovery rates and quality of the end products.

1.3.2 Optimising use of the forest resource

In order to optimise use of forest resources, an understanding of the characteristics of available raw materials and how these impact on production efficiency and the quality of end products is required. The ability to quantitatively predict wood characteristics within the forest resource is becoming increasingly important in the face of rising costs, decreasing land availability and growing demand for sustainably produced and diverse end products (Colin *et al.* 2015; Malan 2003). Such predictive ability would have two main applications. Firstly, the ability to predict internal wood properties like density, MFA and MOE_d and their within-tree variation, would permit allocation of harvested logs to different processing treatments and end products in accordance with log characteristics and the end-product requirements (Malan 2003; Wessels *et al.* 2011; Zobel and van Buijtenen 1989b). Secondly, characterising the spatial variation in wood properties across the available forestry resource would allow forest managers to optimise harvest and transport operations, which are recognised as one of the most important costs of production in the forestry industry (Borges *et al.* 2014).

The ability to understand and predict the variation in wood properties, both within logs and among plantation sites, is contingent upon the ability to accurately measure these wood properties. Measurement of wood properties is discussed in Section 1.3.2.1, followed by a more detailed discussion of how these measurements may be used to develop predictive models of radial and geographic variation in these properties throughout the forest resource.

1.3.2.1 Measurement of wood properties used in characterising logs and forest resources

Depending upon the scale at which measurements are being undertaken, the traditional measurement of wood properties can be expensive and time consuming. For example studies of the radial variation in wood properties is labour intensive as

microscopic measurements of wood fibres are often involved (Downes *et al.* 1997). Density was one of the first wood properties to be studied in detail as it is relatively cheap and easy to measure, and is often correlated with other wood properties and product performance (Downes *et al.* 1997). In addition some methods involve destructive sampling, thus precluding the reuse of samples. However, techniques have been modified and alternative techniques developed or adjusted to address this problem.

SilviScan has been specifically developed for the measurement of wood properties through the radius of the stem, while Near infrared spectroscopy (NIR) calibrations are based on adjusting existing techniques for evaluating chemical components of materials. Both techniques aim to non-destructively evaluate wood properties and to improve the cost-benefit ratio of performing these analyses. The use of SilviScan and potential use of NIR calibrations in measuring the wood properties of *E. nitens* is investigated in Chapter 3.

SilviScan

SilviScan (Figure 1.6a) is a non-destructive tool that analyses the wood microstructure through the radius of the stem. It is capable of assessing wood properties including density, MFA, radial fibre diameter and ring angle. SilviScan scans radial samples which can be obtained from 12 mm cores or disks. Samples must be dried, which is usually done using successive ethanol baths to avoid collapse and then a period of air-drying, resulting in approximately 8% moisture content (Evans 2008).



Figure 1.6 a) SilviScan, b) FT-NIR Spectrometer, and c) Radial transport system for NIR radial scanning of cores and strip samples.

Density is obtained using an X-ray densitometer, and MFA with an X-ray diffractometer, with a maximum resolution for density of 0.025 mm and 1 mm for MFA. Modulus of elasticity is calculated indirectly using density and MFA data at the resolution of the MFA data, following the semi-empirical equation (Evans 2008):

$$MOE = A(I_{cv}D^B)$$

where:

D is air-dry density determined by X-ray densitometry,

I_{cv} is the coefficient of variation of the amplitude of the azimuthal X-ray diffraction intensity profile,

A is a scaling factor (~ 0.165), and

B is an exponent to allow for curvature (~ 0.85).

It is relevant to clarify that the measurement units of density, MFA and modulus of elasticity obtained by SilviScan are: air-dried density in kg m^{-3} , the standard deviation of azimuthal diffraction profile in degrees, and the dynamic modulus of elasticity (MOE_d) in GPa, respectively (Evans 2008).

Although air-dried density is less commonly used in research than basic density, Hamilton *et al.* (2008b) found a very strong correlation ($r=0.997$) between basic and air-dried density. According to Donaldson (2008) SilviScan is perhaps the most commonly used technology globally to assess MFA due to the accuracy of its measurements. In the case of *E. nitens*, density and MFA account for 92% of the variation in MOE_d obtained using a bending test (Yang and Evans 2003). Thus, unless otherwise stated, the terms density, MFA and MOE_d refer to air-dried density (~8% moisture content), microfibril angle and dynamic modulus of elasticity, respectively.

Near Infrared (NIR)

Near infrared (NIR) technology (Figure 1.6b and c), which uses the reflected spectra of emitted electromagnetic radiation in the near infrared range to determine the chemical and physical properties of the sample, has also been used for the non-destructive measurement of wood and forest products (Naes *et al.* 2002). This technique requires calibration of NIR spectra against known properties (usually using partial least squares regression (Wentzel-Vietheer 2012), such as those obtained using SilviScan, but subsequent NIR measurements can then be made at a fraction of the cost of SilviScan measurements (Downes *et al.* 2009b; Schimleck 2008). This method has yielded strong and reliable relationships for cellulose content, but NIR calibrations for density, MFA and MOE_d have shown lower explanatory power, probably as these measures are not as strongly related to wood chemistry and the associated reflectance of NIR radiation (Wentzel-Vietheer 2012).

1.3.3 Radial variation of wood properties from logs of *E. nitens* plantations

As discussed in Section 1.2, wood properties vary between corewood and outerwood, leading to radial variation in these properties perpendicular to the longitudinal growth direction of the tree (Figure 1.7). The importance of this radial

variation in wood properties depends on the target end-product. In the case of engineered wood products, such as plywood and laminated veneer lumber, threshold minimum values in mechanical wood properties are defined by industry standards or end-users.

The ability to estimate the proportion of a log, tree or stand with appropriate wood properties would help optimize the use of raw material, thus impacting the final cost of products, the value of logs and ultimately forest value (Lachenbruch *et al.* 2011; McGavin *et al.* 2014a; West 2014; Zhao *et al.* 2007). In addition, as discussed in Section 1.3.1, knowledge of the wood properties present in a forestry resource are crucial for predicting the wood behaviour and performance during processing, and for understanding the performance of the end product under operating conditions (Bucur 2003). This understanding is therefore essential for the design and development of new wood-based products and advanced engineering designs (Bucur 2003).

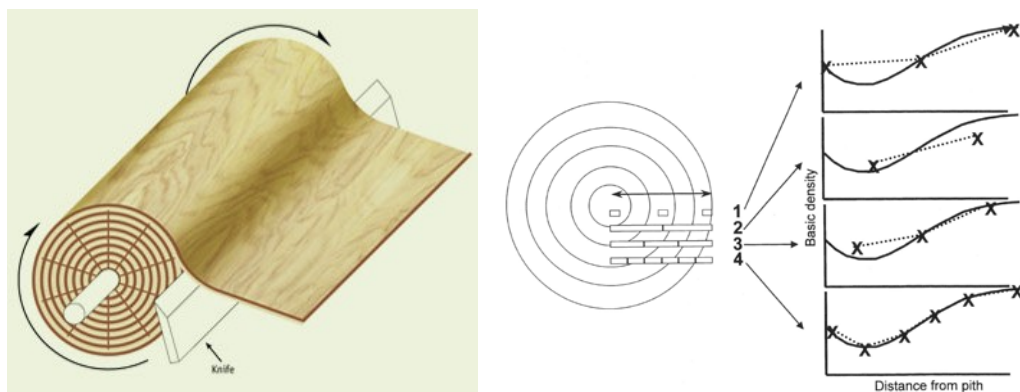


Figure 1.7 Relationship between the peeling process and the scale of measurement of radial variation of wood properties, modified from Downes *et al.* (1997)

In Chapter 4, models to predict the radial variation of density, MFA and MOE_d in *E. nitens* logs were developed. Again, there was a strong effect of site, indicating that environmental and silvicultural factors have a strong influence over these properties.

1.3.4 Forest characterisation of Tasmanian *E. nitens* plantations

There is often a large level of variation in wood properties among plantation sites (Zobel and Buijtenen 1989b) which can significantly influence the recovery and quality of veneers. Understanding how geographic variation (and the associated variation in growing conditions, silvicultural management and genetic factors) influences these wood properties is therefore essential to be able to optimise the use of available resources and improve the competitiveness of forestry industries (Lessard *et al.* 2014; Malan 2003; Payn *et al.* 2015).

The high cost and logistic constraints of directly measuring wood properties across forest resources means that predictive models are required to accurately and efficiently predict these properties. To date, no models capable of predicting *E. nitens* wood quality at a regional scale are available. On the other hand, in conifers there have been several regional characterisation studies in New Zealand and the southeastern United States where different wood properties were evaluated (Antony *et al.* 2011; Jordan *et al.* 2008; Moore *et al.* 2014). Indeed, one of the most comprehensive regional forest characterisation models with several wood properties evaluated was for Canadian conifers, as shown in Figure 1.8 (Lessard *et al.* 2014).

The development of such models is a priority for the industry as improving predictability of the resource is becoming increasingly important for sustainable and efficient use of available natural resources (Malan 2003; Moore and Cown 2015a). These models can be used to characterise existing plantation resources but also to predict the properties of future plantings, thus allowing for more precise planning of future forestry resources. In Chapter 5, forest characterisation models for

density, MOE_d and MFA for *E. nitens* plantations in Tasmania are developed.

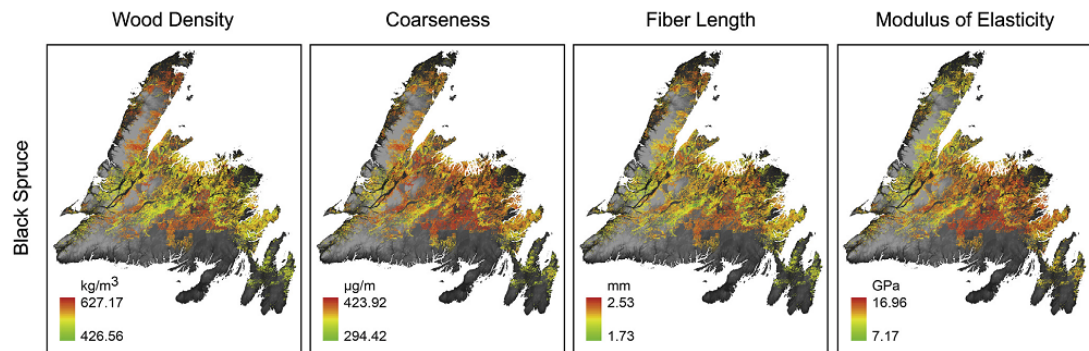


Figure 1.8 Examples of spatial representation of wood properties throughout Canadian conifer forests, modified from Lessard *et al.* (2014)

1.4 Aims of thesis

In summary, for Tasmanian plantation-grown *E. nitens* this thesis has the following four principal aims relevant to the production of structural veneer:

- quantify the development of log-end splitting with storage time and a pre-peeling steam treatment (Chapter 2);
- develop NIR calibrations models for multi-site assessment of density, MFA, and MOE_d (Chapter 3);
- develop and compare models of radial variation in density, MFA, and MOE_d across three sites (Chapter 4); and
- characterise the variability in density, MFA, and MOE_d in the plantation resource across Forestry Tasmania's estate (Chapter 5).

Chapter 2 Influence of site, storage and steaming on *Eucalyptus nitens* log-end splitting

Vega M, Hamilton M, Blackburn D, McGavin R, Baillères H, Potts B (2015) Influence of site, storage and steaming on *Eucalyptus nitens* log-end splitting. *Annals of Forest Science* (DOI 10.1007/s13595-015-0496-3).

2.1 Introduction

There are over 20 million ha of eucalypt plantations in the world (Iglesias-Trabado and Wilstermann 2009). While most eucalypt plantations are grown for pulpwood, 1.2 million ha are managed for sawlog production (FAO 2005). Log-end splitting is one of the many factors affecting the recovery of timber and veneer from plantation-grown eucalypts (Bariska 1990; Chauhan *et al.* 2006b; Priest *et al.* 1982; Yang *et al.* 2005). It manifests immediately after felling and tends to increase further with time in storage.

Log-end splitting occurs as a consequence of growth stress (Kubler 1987). Growth stress is generated during cell maturation in the cambium zone (Yang *et al.* 2005). These forces produce tension in the cells near the cambium, while the cells near the pith are in compression. This contrast generates a residual stress distribution (Chauhan *et al.* 2006b; Kubler 1987; Okuyama 1997). When a tree is felled or a log is cross-cut, the elastic energy of the residual stress is released through formation of end splits at the crosscut surface (Okuyama 1997). In the absence of drying with shrinkage, cross-cutting creates a free surface in a pre-stressed volume (growth stress field) which leads to a redistribution of stresses. On a log end this is equivalent to axially pulling its centre and applying a pressure on its periphery (Archer 1987). These forces induce heart splitting when the radial stress generated by the redistribution reaches the ultimate strength of green wood in the tangential direction. From a solid mechanics point of view the initiation and progression of the cracks depend on the geometry of the log, the field of growth stresses, the elastic and non-elastic mechanical properties and transverse strength or toughness of

green wood (Jullien *et al.* 2003). The later mechanical properties, tangentially to the log axis, can be significantly affected by grain angle along with the end-split pattern.

Growth stress and consequently log-end splitting varies within and among trees, as well as among sites, and are potentially influenced by genetic, environmental and silvicultural factors (Archer 1987; Kubler 1988). Genetic effects in *Eucalyptus*, for example, have been reported at the clonal (Malan and Verry 1996), family (Barros *et al.* 2002), provenance and species levels (Nixon 1991). In addition, Nixon (1991) found that *E. nitens* showed the lowest level of splitting when it was compared among 13 different eucalypts species in South Africa. Environmental factors which can increase growth stress include those which cause stem re-orientation, such as slope, aspect and wind exposure (Archer 1987; Kubler 1987; Malan and Verry 1996). These factors affect the manner in which the stem and crown are oriented, inducing a redistribution of internal growth stress in the stem (Kubler 1988; Mattheck and Kubler 1997). Wind pressure, for example, has been observed to promote splits at right angles to the main wind direction (Mattheck and Kubler 1997).

Silvicultural practices can also influence the magnitude of growth stress (Malan 1995). Thinning is the most important silvicultural intervention in terms of its effect on growth stress and log-end splitting because it affects competition among trees. Thinned stands, which experience lower competition, produce trees with high taper and large crown which tend to exhibit low growth stress (Mattheck and Kubler 1997). In contrast, trees under strong competition have slender stems, narrow crowns and exhibit high levels of growth stress (Becker and Beimgraben 2002). However, the effect of competition on growth stresses may change with development stage of the stand (Biechele *et al.* 2009). When thinning is frequent and light, trees do not need to re-orientate their crowns to catch light, so growth stresses are likely to be lower. On the other hand, infrequent and heavy thinning results in drastic changes in the amount and direction of light which may lead to high growth stress (Kubler 1988).

In addition to these genetic, environmental and silvicultural influences on growth stress, there are industrial factors that directly affect the magnitude of log-end splitting during processing. In veneer processing the most relevant factors are storage time and log heating. Logs are commonly stockpiled to avoid production stoppages, or to buffer the production system against market-price fluctuations (Shmulsky 2002). In eucalypt logs, two phases of split development during storage have been described (Bariska 1990 ; Priest *et al.* 1982). The first phase starts immediately after felling, with splitting increasing rapidly until 6 to 20 days after felling. This is followed by a second phase when splitting is significantly slower. In terms of the wood supply chain, the first splitting phase usually occurs between felling and the log yard, whereas the second phase is usually evident after storage in the log yard prior to processing.

Heating hardwood logs using hot water or steam is common practice prior to peeling for veneer (Shmulsky 2002). This is done to improve veneer yield, smoothness and thickness uniformity and to reduce energy consumption (Becker and Beimgraben 2002 ; Dupleix *et al.* 2012). In species prone to developing high growth stresses, log heating has been reported to relieve growth stresses and improve timber quality (Severo *et al.* 2010). However, heating logs at high temperatures can also exacerbate log-end splits (Marchal *et al.* 1993). This is believed to be due to the expansion and contraction of wood associated with heating and cooling - a phenomenon called hygrothermal recovery (Kubler 1987). Tangential dimensional change in the wood is the most important driver of log-end splitting, as it is far greater than radial and longitudinal dimensional changes (Kubler 1987; Marchal *et al.* 1993). The magnitude of split propagation within a log not only depends on the inherent growth stresses, but also the temperature and duration of heating (Becker and Beimgraben 2002; Dupleix *et al.* 2012; Gril and Thibaut 1994; Marchal *et al.* 1993).

The present study aimed to evaluate the relative importance of the above factors on the magnitude of log-end splitting using Tasmanian plantations of *Eucalyptus nitens* (Deane and Maiden) Maiden. Plantation-grown trees of this species can produce log-end splits when felled and crosscut into logs (Blackburn *et al.* 2011;

Valencia *et al.* 2011). *Eucalyptus nitens* is widely planted in temperate regions of the world (Hamilton *et al.* 2011) and is the second most prevalent hardwood plantation species in Australia (Gavran 2014). Within Tasmania, there are approximately 208,400 ha of *E. nitens* plantations (Gavran 2014; Hamilton *et al.* 2008a) which are mainly managed for pulpwood. Fifteen percent of these plantations, however, have been pruned and thinned to produce high quality logs for sawing and/or veneer production (Forestry Tasmania 2011). It is anticipated that these pruned and thinned plantations will be used by Tasmania's forest processing industries along with traditional sources of hardwood logs from the island's native forests (Forestry Tasmania 2011).

A few studies have investigated factors affecting log-end splitting or growth stresses in *E. nitens*. With respect to genetic factors, Blackburn *et al.* (2011) showed that trees grown in a Tasmanian trial of families from different geographic races exhibited significant genetic variation in log-end splitting within the races. However, no significant genetic difference has been reported between races of this species (Blackburn *et al.* 2011). In terms of silviculture, Valencia *et al.* (2011) showed that thinning to different spacings did not affect log-end splitting after accounting for the positive effect of stem diameter. Several recent studies of Tasmanian *E. nitens* have shown log-end splitting increases with height up the tree (Blackburn *et al.* 2011; Valencia *et al.* 2011). We are not aware of any previous studies investigating the effect of post-felling treatments, such as storage and steaming on log-end splitting for *E. nitens*.

The specific objective of this study is to quantify the development of log-end splitting in plantation-grown *E. nitens* and determine the influence of:

- site, log position, diameter, and inter-tree competition;
- log storage time; and
- a pre-peeling steam treatment.

Improved understanding of the factors that determine log-end splitting will contribute to improved use of the *E. nitens* plantation resource and ultimately to more effective forest management.

2.2 Materials and methods

2.2.1 Field sites and tree selection

Three contrasting *E. nitens* plantations at Strathblane, Geeveston and Florentine in the south of Tasmania (Australia) were selected for study (Table 2.1). These *E. nitens* sites belong to Forestry Tasmania and were previously included in multi-species studies of veneer recovery and quality (Hamilton *et al.* 2014; McGavin *et al.* 2014b). They encompassed different silvicultural treatments and/or site productivities: Strathblane and Geeveston were thinned and pruned for solid wood production but differed markedly in productivity. The Florentine site was an unthinned and unpruned pulpwood stand. Within each site a measurement plot (972.3 to 2156 m²) was established and basal area within plots determined. Trees for felling were then selected at random within plots, excluding trees of less than 220 or greater than 390 mm in diameter breast height over bark (DBH; 1.3 m) or with any evident visual defects such as double leaders. At the Geeveston site no maximum DBH criterion was applied as trees were too large and a representative sample could not be obtained within these log size constraints. Following Medhurst *et al.* (2012), intra-specific competition for each tree was quantified as the sum of the basal areas of competing trees located within a 6 m radius of each sampled tree.

Table 2.1 Characteristics of the three *Eucalyptus nitens* plantations sampled

Sites	Strathblane	Geeveston	Florentine
Location and environment			
Latitude & Longitude (°)	-43.38; 146.94	-43.15; 146.84	-42.66; 146.47
pMAI (m ³ /ha/year) ^a	20.8	36.6	37.2
Site index	22.7	30.3	30.5
Altitude (m above sea level)	153	296	438
Annual mean temperature (°)	10.9	10.3	9.5
Minimum temp. coolest month (°)	3.4	2.2	1.2
Annual rainfall (mm)	1161	1212	1436
Annual evaporation (mm)	963	929	913
Soil description	Sandy over clayey	Loamy over clayey	Yellow podzolic

Sites	Strathblane	Geeveston	Florentine
			(gradational)
Soil profile	Triassic sandstone- sandy over clayey soil	Red to brown clayey soils- Jurassic dolerite and Quaternary dolerite talus	Yellowish brown clay- mudstone, brown kurosol
Wind direction	Generally northwest and site has intermediate exposure	Generally north west and site is exposed	Generally south west and the site has intermediate exposure
Silviculture			
Year of establishment	1993	1991	1993
Genetic origin	n/a	n/a	n/a
Management	Thinned and pruned	Thinned and pruned	Pulp
Establishment spacing (tree by row in m)	2 by 4	2.5 by 3	2 by 4
Establishment density (stems ha ⁻¹)	1250	1334	1250
Age at thinning (retained stems ha ⁻¹)	11 (300)	10 (192)	Unthinned
Age at pruning (height, m)	3 (unknown) and 5 (6 m)	4 (unknown) and 6 (6 m)	Unpruned
Harvest characteristics			
<i>Plot-level data</i>			
Felling age (years)	20	22	20
Harvest stocking (stems ha ⁻¹)	292	196	669
DBH ^b (cm)	31.2	43.1	26.9
Basal area (m ² ha ⁻¹)	23.2	30.3	41.3
<i>Selected trees</i>			
DBH ^b (cm)	30.0	42.7	33.9
Height (m)	26.9	37.5	36.4
Slenderness ^c	90.5	92.0	107.8
Mean log diameter (cm)			
– lower	27.2	39.3	32.3
– upper	23.1	35.8	29.3

^a peak Mean Annual Increment. ^b Diameter at breast height over bark. ^c Height/DBH

2.3 Preparation and log measurement

All trees were manually felled by the same operator and height measured from the felled tree. Two 2 m logs were cut from each tree. The lower log started at 0.5 m and the upper log at 3.9 m above ground level. Logs were transported to a local storage facility at Geeveston on the same day as felling, where they were debarked and measured. Small end diameter under bark (SEDUB) and large end diameter under bark (LEDUB) were assessed on each log using a diameter tape. The length of log-end splits were measured on each log end as well as the length of split on the log surface. Log-end splitting was evaluated with two indices, Split Index-2 (SI-2) and maximum split length on the log surface. Split Index-2 is described by Yang (2005) and integrates all splits present in the log, weighted by the mean radius of the log (Appendix B). The maximum split length was evaluated across either end of the log. After measurement, log ends were sprayed with sealant (Dussek-Campbell TM) to minimise moisture loss. Logs were then stacked in a shipping container for transport to a research-scale peeling plant at Salisbury, Queensland. To minimise drying, logs were sprayed with water, prior to transport in the shipping container and while in storage at Salisbury.

2.3.1 Assessments

Log-end split evaluations were made at three times (Figure 2.1). The first was 24 hours after the trees were harvested, hereafter referred to as the ‘post-felling’ assessment. The second was during two days, starting the day after logs arrived at the peeling plant (13 and 14 days after the harvest) and is hereafter referred to as the ‘log-yard’ assessment. The third (‘pre-docking’) assessment was undertaken just before peeling. Logs from the Geeveston site were not included in the third assessment as a number of logs were too large for peeling in Salisbury research facilities and were moved to a nearby commercial facility for peeling. The remaining logs (Strathblane and Florentine) were allocated to one of two groups - steamed or not steamed (31 logs per group). One log from each tree was randomly allocated to each group. The steaming treatment is described by McGavin *et al.* (2014b). Briefly,

prior to peeling 2 m logs were steamed in batches of (usually) six randomly chosen logs, with all batches processed over a period of seven working days (25 – 33 days after harvest). The logs were heated with saturated steam at 80°C for approximately eight hours. Generally six randomly selected steamed logs and six unsteamed logs were peeled each day. The pre-docking assessment was undertaken immediately after the steam treatment, but in this case only the maximum split length on the log surface was assessed, to avoid temperature loss prior to log peeling. The same evaluation was made on the sample of unsteamed logs being processed on the same day.

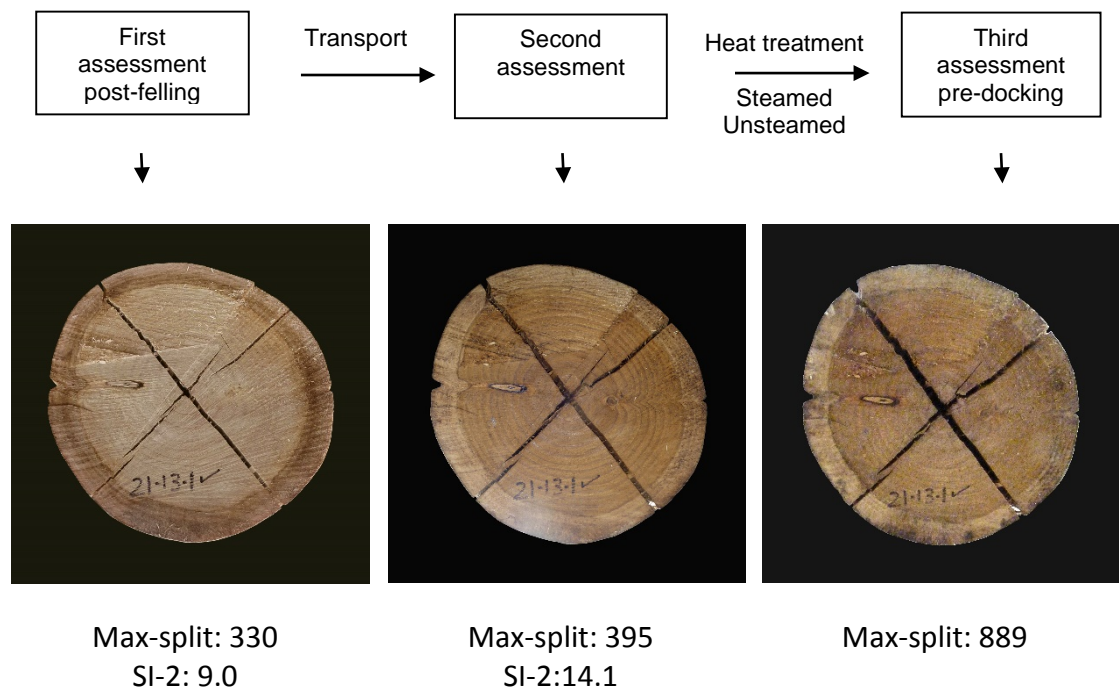


Figure 2.1 The sequence of assessments undertaken according to days from harvest.

Photographs show the development of log end splitting in each assessment for a log exhibiting a high level of splitting. The log was from the Florentine site and was steamed. The maximum surface split (max-split, mm) and Split Index 2 (SI-2) for each assessment is indicated.

2.3.2 Data Analysis

Both splitting measures were log transformed ($\text{Log}_{10}[x+1]$) for analysis, as preliminary analyses of raw log-level data revealed that the distribution of residuals were neither normal nor homoscedastic.

Models involving various combinations of site, assessment time, log position and covariates were fitted to the splitting data using a restricted maximum likelihood approach implemented with the PROC MIXED procedure of SASTM (Version 9.2, SAS Institute, Cary, USA). Fixed effects were tested using Type III F tests.

Repeated measures models (Wolfinger and Chang 1995) were used when fitting assessment time or log position, with tree the subject.

Specific models fitted to the pre-steaming splitting data were based on tree-level (average of both logs) or log-level data and included:

- a repeated measures model fitting site (three fixed levels), assessment time (two fixed levels) and their interaction (six fixed levels) to the tree-level data with tree the subject; and
- a repeated measures model fitting site (three fixed levels), log position (two fixed levels) and their interaction (six fixed levels) to the log-level data with tree the subject.

To examine the effect of intra-specific competition for each tree (surrounding basal area) and focal tree DBH and slenderness (Height/DBH) on log-end splitting, a fixed effects model as previously described was fitted to the tree-level data that also include basal area of surrounding trees as well as DBH or slenderness of the focal tree and their interaction as covariates.

In addition to the fixed explanatory variables mentioned above, the same type of model was fitted to determine the influence of the time between first and second assessments.

2.4 Results

2.4.1 Site differences and storage

Analysis of the tree-level SI-2 data revealed that log-end splitting significantly increased between the post-felling and log-yard assessments (Time $F_{1,39}=123.6$, $P<0.001$; Figure 2.2a). Over this period the average SI-2 increased by 96.6%. This increase was not significantly different between sites (Site x Time $F_{2,39}=0.5$, $P\geq 0.05$), however the sites themselves differed significantly (Site $F_{2,39}=12.1$, $P<0.001$). Log-end splitting was lowest in logs from the low altitude, low-productivity site at Strathblane which had been thinned and pruned, and greatest in the logs from the thinned and pruned, mid-altitude, high-productivity site at Geeveston (Figure 2.2a). These temporal and site differences were evident whether splitting was assessed using SI-2 (Figure 2.2a) or as a percentage of logs showing surface splits (Figure 2.2b). Site differences were also clearly evident when log-level data was analysed at the separate assessment times, and evident in the upper or lower log (Table 2.2, Figure 2.2).

While there was no significant difference in SI-2 between upper and lower logs immediately following harvesting (post-felling), differences in SI-2 did become evident with time after transport and storage (Table 2.2). Between the post-felling and log-yard assessments, SI-2 of the upper logs increased 141% and the lower logs increased 88%.

The Site x Log position interaction was not statistically significant (Table 2.2). Nevertheless, the increased splitting in upper logs following storage (post-felling versus log-yard assessments) was most evident in trees from the two pruned and thinned sites (Strathblane and Geeveston - Figure 2.2a). At this stage all logs from Geeveston had surface splits, but for Strathblane only 43% of the lower logs had surface splits compared with 71% of the upper logs (Figure 2.2b).

Table 2.2 Significance of site and log position on log-end splitting (SI-2) at post-felling and log-yard assessments. The F values and their significance for each assessment are shown. A repeated measures model was fitted to log-level means with site (ndf = 2), log position (ndf = 1) and their interaction fitted as fixed terms. The denominator degrees of freedom range from 38 to 40.

Fixed terms	F value	
	Post-felling	Log-yard
Site	13.4***	10.4***
Log position	0.0ns	6.7*
Site x Log position	0.5ns	2.4ns

^{ns} Not significant, * P < 0.05, ** P < 0.01, *** P < 0.001

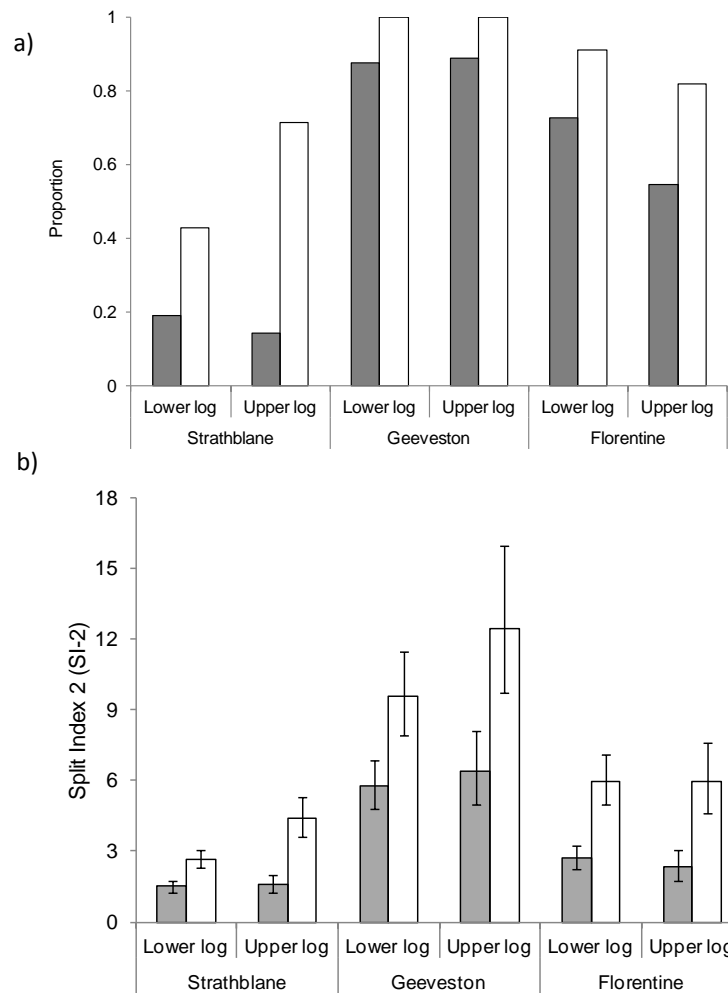


Figure 2.2 Site by log position a) least squares mean (\pm s.e.) Split Index 2 (SI-2) following back-transformation, and b) the proportion of logs with surface splits. The post-felling (grey) and the log-yard (white) assessments are shown for upper and lower logs for each site.

2.4.2 Silviculture differences

Despite the fact that sites differed markedly in the competitive environment and DBH of felled trees (Table 2.1), these factors did not completely explain the significance of the effect of site-of-origin on log-end splitting. When it was tested as a covariate in a tree-level model which included site and interaction terms, the competitive environment of a tree (intra-specific competition) had no significant effect on SI-2. This was the case for both the main covariate effect and its interaction with Site, post-felling ($F_{1,30}=0.28$, $P\geq 0.05$; interaction with Site $F_{2,30}=0.19$, $P\geq 0.05$) and in the log-yard ($F_{1,30}=0.29$, $P\geq 0.05$; interaction with Site $F_{2,30}=0.31$, $P\geq 0.05$).

Dropping the competition covariate and its interaction with Site and fitting a reduced model revealed that standing-tree DBH significantly affected splitting. However, this relationship was site dependent, with a significant DBH x Site interaction for both post-felling and log-yard SI-2 (Table 2.3). This interaction was due to a significant positive relationship between SI-2 and DBH at the high-altitude Florentine site which was unpruned and un-thinned (post-felling $R^2 = 59.8\%$ $P<0.01$; log-yard $R^2 = 50.7\%$ $P<0.05$). However, at the two pruned and thinned sites, DBH did not explain significant variation in SI-2 amongst trees (Strathblane, post-felling $R^2 = 3.7\%$ $P=0.404$, log-yard $R^2 = 0.4\%$ $p=0.785$; Geeveston, post-felling $R^2 = 7.3\%$ $P=0.449$; log-yard $R^2 = 0.09\%$ $P=0.933$). Even when accounting for tree DBH and its interaction, there still remained a significant main effect of site on SI-2 (Table 2.3).

Similar conclusions are reached when fitting tree height which was slightly more strongly associated with the splitting index than DBH, with the exception of the post-felling splitting index where the significance of the site effect was reduced slightly ($P<0.1$). Tree slenderness had no significant ($P>0.05$) effect on the post-felling or log yard splitting in any model.

Table 2.3 Significance of site and diameter at breast height over bark (DBH) on log-end splitting (SI-2) at post-felling and log-yard assessments. The F values and their significance for each assessment are shown. The model was fitted to tree level means with Site (degrees of freedom = 2) as a fixed effect and DBH as a covariate (degrees of freedom = 1). The denominator degrees of freedom for all terms is 36.

Fixed terms	F value	
	Post-felling	Log-yard
DBH	11.5*	5.8*
Site	5.0*	4.8*
DBH x Site	4.3*	4.8*

^{ns} Not significant, * P < 0.05, **P < 0.01, ***P < 0.001

2.4.3 Steam treatment

As a consequence of time constraints imposed by veneer processing, the evaluation of the effect of steaming on splitting was conducted based on the maximum surface split length of each log rather than SI-2. However, maximum surface split length and SI-2 of logs were positively associated (Figure 2.3). There was no significant difference in maximum surface split length on logs treated with steam compared with those not treated (Table 2.4). The differences in splitting between samples were simply an extension of pre-steaming storage effects, as were the slight increases between the log-yard and pre-docking assessments (Figure 2.4 and Figure 2.5). Despite only logs from the least differentiated sites (Strathblane and Florentine) being studied, site-of-origin effects were still evident in steamed and unsteamed treatments prior to docking (Table 2.4, Figure 2.4 and Figure 2.5).

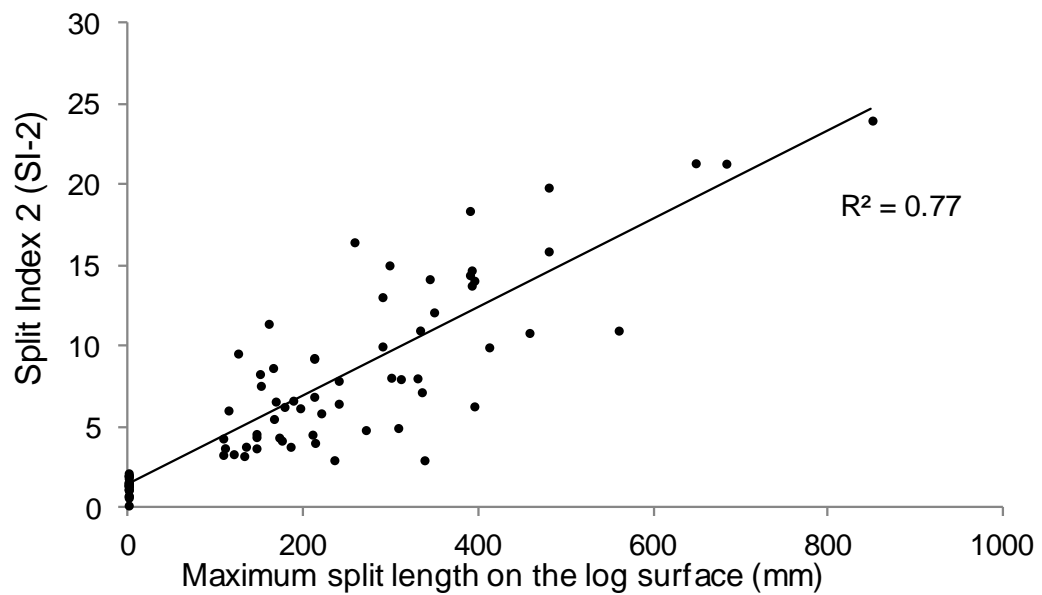


Figure 2.3 Linear regression analysis between Split Index 2 and the maximum split length on the log surface as assessed in the log yard (without the zero values in maximum split length $R^2=0.64$)

Table 2.4 Significance of factors affecting maximum surface splitting in the pre-docking assessment. A repeated measures model was fitted to log-level data with site, log position, steam treatment and their interaction fitted as fixed terms. The $F_{1,54}$ values and their significance for each assessment are shown. Data are from the Strathblane and Florentine sites only.

<i>Fixed terms</i>	<i>F value</i>
Site	6.9*
Log position	0.4 ^{ns}
Site x Log position	1.5 ^{ns}
Steam treatment	0.1 ^{ns}
Steam treatment x Site	0.1 ^{ns}
Steam treatment x Log position	0.6 ^{ns}
Steam treatment x Site x Log position	2.9 ^{ns}

^{ns} Not significant, * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

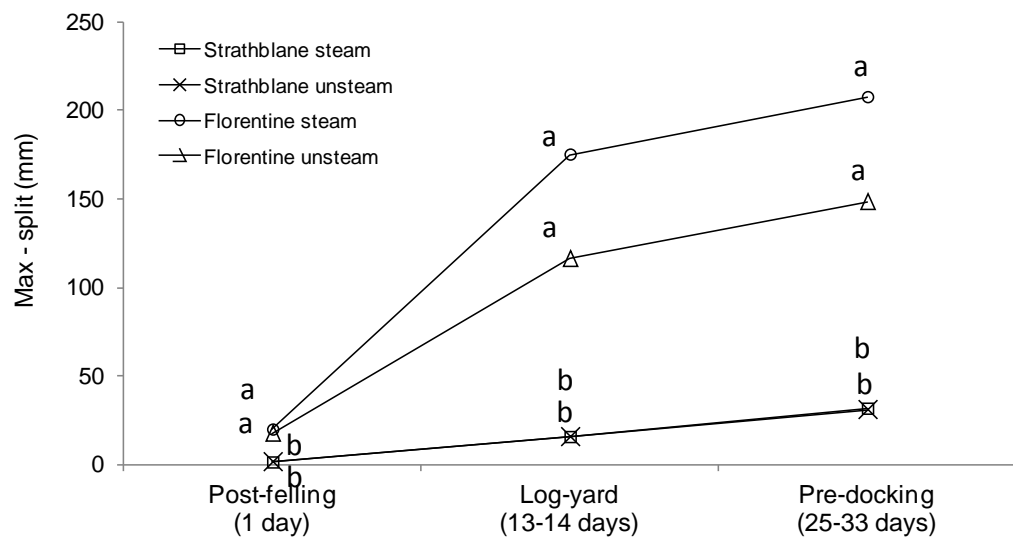


Figure 2.4 Development of maximum split length on the log surface (Max-split, mm) of the steamed and unsteamed log samples from Strathblane and Florentine. Back-transformed least-square mean values are shown for the three assessments (post felling, log yard, pre docking). Steaming occurred just before the pre docking assessment. Common letters indicate means where the pair-wise LSD is not significant different at the 0.05 level.

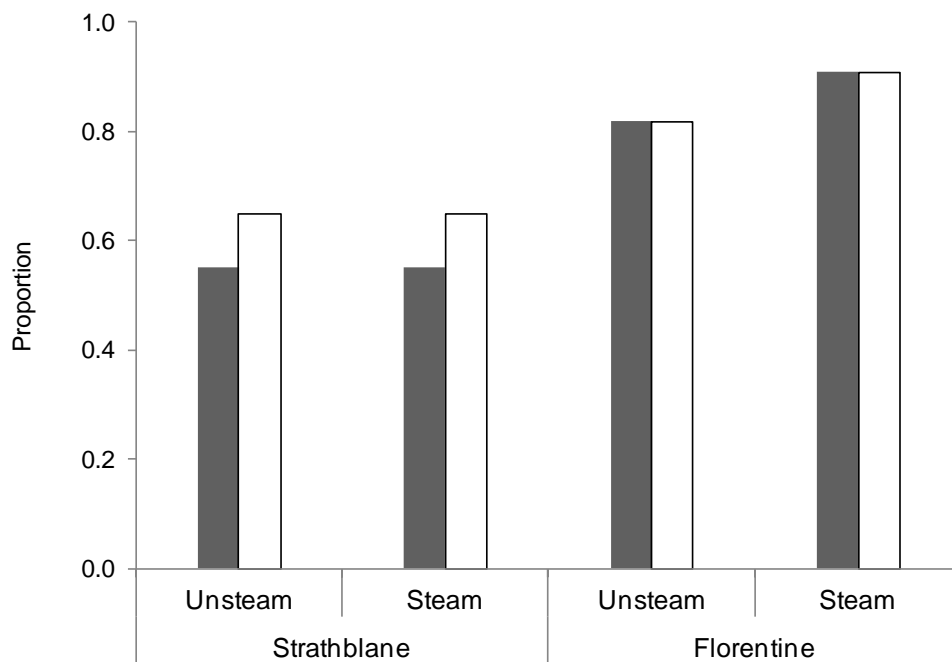


Figure 2.5 The proportion of steamed and unsteamed logs from the Strathblane and Florentine sites with surface splits in the log yard (grey) and in the pre-docking assessment (white) undertaken after steaming.

2.5 Discussion

A key finding of this study was the identification of site-of-origin as being an important factor contributing to variation in the log-end splitting of these plantation-grown trees of a single species. This effect was evident immediately after felling in both upper and lower logs, and was maintained along the processing chain and still evident after accounting for variation in DBH. The site mean SI-2 values differed by up to 39.3% depending upon log storage time and position, and the values of our least split sites were most comparable with the site mean reported by Valencia *et al.* (2011) for 22-year old *E. nitens* grown in northeast Tasmania. The exact causal factor(s) underlying these site differences can only be speculated, as there are clearly both environmental and silvicultural differences amongst these sites. In addition, the possibility of differences in log end-splitting due to genetic stock cannot be dismissed. However, most Tasmanian *E. nitens* plantations established approximately 20 years ago were established from open-pollinated seed from Central Victoria (Hamilton and Potts 2008), and genetic differences due to race of origin are unlikely as no race differences within this region were detected in an *E. nitens* genetic trial grown in Tasmania (Blackburn *et al.* 2011).

Our study included both thinned (and pruned) and un-thinned plantation sites, but these differences alone are unlikely to explain the site differences we observed for several reasons. Firstly, no significant effect of thinning *per se* on log-end splitting has been reported in an *E. nitens* thinning trial (Valencia *et al.* 2011). Secondly, within sites there is no significant effect of intra-specific competition at the time of harvest on log-end splitting (present study) or indirect measures of growth stress (Valencia *et al.* 2011), although the influence of the competitive environment at earlier ages cannot be dismissed (Biechele *et al.* 2009). Finally, although there are only slight differences in the age of thinning and pruning, there is a significant difference between the two thinned sites, with the logs from the Geeveston site having significantly greater log-end splitting than the Strathblane site.

Of the environmental factors which differ between Strathblane and Geeveston, greater exposure to prevailing winds is a possible explanation of the greater

splitting in logs from Geeveston, especially when coupled with higher site productivity and late thinning when 10 years old (Malan 1995). Wind can produce high growth stress (as measured indirectly from peripheral longitudinal growth strain) on the leeward side of *E. nitens* trees (Valencia *et al.* 2011), and can also result in an asymmetrical crown that may further increase growth stresses (Becker and Beimgraben 2002). A positive relationship between growth stress and tree slenderness has been reported in *Fagus sylvatica* (Jullien *et al.* 2013). However, this species has quite different architecture to *E. nitens* being two-fold less slender, and the variation among tree slenderness was unrelated to log-end splitting in the case of *E. nitens*.

Our finding that log-end splitting in *E. nitens* significantly increased with increasing height up the stem was consistent with that found by Valencia *et al.* (2011) for Tasmanian grown *E. nitens*, although in their case the difference was manifest immediately after felling. The trend for log-end splitting to increase with tree height in thinned (and pruned) plantations is contrary to the expectation based on DBH, as the smaller upper logs split more than the larger lower logs. Valencia *et al.* (2011) suggest that this trend may be due to a greater level of growth stress at greater heights. Consistent with this hypothesis, based on studies of several eucalypt clones Baillères (1994) reported that peripheral longitudinal growth stress tends to increase in the vicinity of living branches and is higher close to the crown, allowing the tree a more efficient control of the crown position. Valencia *et al.* (2011) also raised the possibility that the greater log-end splitting they observed in the upper log could be due to greater bending of the upper part of the tree during mechanical harvesting. However, the present study suggests this is not a contributing factor as, firstly, our trees were not mechanically harvested and, secondly, the difference between the upper and lower log tended to increase with storage time.

Storage is a key phase in the processing industry and various approaches have been adopted by processors in an effort to minimize log-end splitting during this period, including the application of a log-end sealer, the use of sprinklers in log yards to keep logs moist, and debarking just after steaming and peeling (Chauhan *et al.* 2006b). While our scoring times do not allow finer resolution of this first period, on

sites prone to log-end splitting there is clearly a rapid early increase in splitting despite the application of a log-end sealer and water to minimise moisture loss. Log-end splitting was similar between lower and upper logs 24 hrs after cross-cutting but became greater in the upper log with storage time. Delayed release of strain may explain the later appearance of a significant difference in splitting between upper and lower logs (Kubler 1987). The increased splitting of upper logs over time could be indicative of higher, longer-lasting compression forces on the upper log wood than on the wood of the lower log, which require more time to release. Boyd and Schuster (1972) found that full release of growth stresses may take two or even three weeks, as did Malan (1995) with *Eucalyptus*.

The general two phase split development described previously (Bariska 1992; Priest *et al.* 1982), was evident in this trial with log-end split development being most rapid between the post-felling and log-yard assessment (13-14 days), and slower between log-yard and pre-docking assessments (12-19 days). The increase in splitting during storage may be due to the delayed release of growth stress as is suggested by Bariska (1992), possibly from a time effect on viscoelasticity properties of green wood (Gril and Thibaut 1994).

The steam heating of logs prior to peeling is a standard practice in the veneer industry, because it improves both the yield and quality of veneer (Dupleix *et al.* 2012). However, steaming may release growth stresses (Severo *et al.* 2010), and potentially promotes log-end splitting (Baldwin 1995a). This effect was not observed in the present study. This is likely due to the fact that logs had an extended storage time, meaning that most of release of growth strain in the logs had been completed prior to steaming. However, as the temperature used to heat the logs was lower than is recommended by Dupleix *et al.* (2012) and Severo *et al.* (2010), we cannot dismiss the possibility that further splitting may have occurred if higher temperatures had been used.

Our demonstration of a relationship between the more detailed split index SI-2 and the quickly assessed maximum split length on the log surface, as previously reported for eucalypts (Bariska 1990), allowed assessment of the change in log-end

splitting during log processing for veneer – following steaming and just prior to docking. However, the impact of the various values of SI-2 and the maximum surface split on the veneer recovery needs further study. While Hamilton *et al.* (2014) did not detect an effect of post-felling SI-2 values on green recovery following docking of these logs for spindleless lathe peeling, this may be more evident later as splitting increases with storage and will depend upon the opportunities for docking of logs prior to peeling. Although logs with lower SI-2 values (less than 3.0) do not have surface splits (Figure 2.3), this does not exclude the possibility that splitting at this level could still reduce veneer recovery in addition to reducing the grade recovery (McGavin *et al.* 2014b). This is because SI-2 assumes that the split shape is an isosceles right-angled triangle which is projected inside the log (Yang 2005). Such splitting would extend most into the residual billet core (target radius of 25 mm in Hamilton *et al.* (2014)), and splitting outside of this could be managed to some extent depending upon the opportunities for docking.

Chapter 3 Development of near-infrared calibrations for the prediction of wood density, micro fibril angle and modulus of elasticity in *Eucalyptus nitens* from Tasmania

3.1 Introduction

Near-infrared spectroscopy (NIR) is an analytical technique that is commonly used to predict the chemical wood properties of standing trees and wood products. Although woodchips (Downes 2011; Schimleck 2008) is one of the most common wood products, NIR has also been applied to map wood chemistry variation over a whole disk (Thumm *et al.* 2010). The usual technique involves extracting a wood sample, which is most commonly ground into woodmeal, and measuring reflectance in the infrared region of the electromagnetic spectrum (700 to 2500 nm) (Osborne *et al.* 1993 cited by Schimleck (2008)). The most useful part of the infrared region for quantitative analysis is the range from 1200 to 2500 nm (Marten *et al.* 1989). The interpretation and analysis of NIR spectra requires the use of multivariate analytical techniques, such as principal components analysis (PCA) and/or partial least squares (PLS), to develop calibrations for the properties of interest (Downes *et al.* 2007). However, once NIR calibration models have been developed they can be applied to predict properties of interest from NIR spectra, with minimal training in the use of appropriate software. Furthermore, it is increasingly recognised that it is possible to develop robust calibrations for chemical properties that can be applied across multiple sites and species (Downes 2011; Downes *et al.* 2007; Downes *et al.* 2011; Downes *et al.* 2010b; Tsuchikawa and Kobori 2015).

Although NIR reflectance is most commonly used to predict chemical wood properties (Tsuchikawa and Kobori 2015), calibrations to predict physical wood properties (e.g. density, shrinkage, microfibril angle [MFA] and modulus of elasticity dynamic [MOE_d]) have been developed (Schimleck 2008; Tsuchikawa 2007; Tsuchikawa and Kobori 2015). Furthermore, automated methods to scan unground

wood samples at regular intervals (e.g. every one millimetre on the radial face of wood samples) have been developed (Hein and Lima 2012; Schimleck *et al.* 2006; Schimleck *et al.* 2002; Wentzel-Vietheer 2012). The ability to scan unground samples in this fashion potentially allows detailed examination of intra-tree variation in wood properties such as radial variation, and provides researchers, wood growers and wood processors with a tool to better characterise timber resources (Lachenbruch *et al.* 2011; Maeglin 1987), rank trees for breeding programs (Downes *et al.* 2010b), optimise the product value through log segregation (Briggs 2010), and understand the impacts of site/silviculture (Downes *et al.* 2014).

With increasing interest in the use of plantation-grown *Eucalyptus nitens* (H.Deane & Maiden) Maiden for solid wood products in Tasmania (ABARES 2014; Forrester *et al.* 2010), the assessment of wood stiffness as measured by Modulus of Elasticity has become an important trait for resource characterisation (Antony *et al.* 2011) and breeding (Blackburn *et al.* 2010). This has been indirectly assessed at a large-scale using acoustic wave velocity of standing trees (Blackburn 2012). Such evaluations, however, are dependent on moisture content which makes the comparison between sites or seasons difficult (Watt and Trincado 2014; Wielinga *et al.* 2009), does not allow study of the radial variation in wood properties, and does not facilitate assessment of other wood property traits that would be possible following scanning for NIR. Other tools have been developed to examine radial variation in physical wood properties, such as image analysis, densitometry, UV and confocal microscopy, X-ray, computed tomography and SilviScan (Donaldson 2008; Wimmer 2008). However, once appropriate NIR calibration models have been developed, NIR analysis is generally cheaper, more rapid, able to predict multiple properties with one operation, and less dependent on highly skilled operators than alternative approaches (Schultz and Burns 1990).

Near-infrared spectroscopy calibration models for the prediction of physical wood properties have been developed for the temperate eucalypt *Eucalyptus globulus* Labill, which include density, MFA and MOE_d (Downes *et al.* 2014; Wentzel-Vietheer 2012). These models were based on the alignment of SilviScan and NIR point data

from scanning of the radial face of air-dried intact radial wood samples from trees from three sites in Western Australia. While the cross validation of these models to an independent site in Victoria did not precisely predict density ($R^2=46\%$) or MFA ($R^2=50\%$), MOE_d was predicted with reasonable precision ($R^2=71\%$) (Downes *et al.* 2014). Consequently we aimed to investigate the use of NIR modelling to predict MOE_d in *E. nitens* and whether meaningful tree-level predictions for density and MFA can be obtained. To undertake large-scale resource characterisation studies examining the influence of environmental and silvicultural factors on wood properties, such NIR models would be required to be applicable across a broad range of *E. nitens* plantations.

3.2 Materials and methods

3.2.1 Trial descriptions

Near infrared spectroscopy calibration models were developed from cores of 12 mm diameter collected from three silvicultural trials, Creekton, Goulds Country (hereafter referred to as Goulds) and Lisle, in May 2006, May 2010 and May 2006 respectively. These trials were established by Forestry Tasmania to evaluate the effects of pruning and thinning on *E. nitens* (Medhurst *et al.* 2001).

The Creekton trial was located in the southeast of Tasmania (43°21' S, 146°54' E) and Goulds and Lisle in the northeast (41°05' S, 148°06' E and 41°13', 147°22', respectively). Site characteristics are summarised in Table 3.1.

Table 3.1 Stand characteristics of the *E. nitens* trials from which wood samples were obtained (Medhurst *et al.* 2001)

Site Characteristics	Creekton	Goulds	Lisle
Plantation management			
Year of planting	1989	1984	1987
Provenance of seed	Upper Toorongo	Upper Toorongo	Upper Toorongo
Tree spacing (m x m)	3.5 x 2.0	3.5 x 2.5	3.0 X 2.4
Plantation density (stems ha ⁻¹)	1430	1143	1389
Mean annual rainfall (mm)	1086	776	1055
Altitude (m a.s.l.)	110	120	220
Inventory on unthinned treatments			
Thinning age (years)	8	6	9
Stems ha ⁻¹	1256	999	1031
Mean height (m)	16.6	11.2	20.2
Mean diameter (cm)	14.5	11.9	18.5
Diameter range (cm)	0.4-27.8	0.5-25.7	2.7-35.2
Mean annual increment at age 9 years (m ³ ha ⁻¹ year ⁻¹)	19.8	10.1	26.2
Year of coring	21	22	19

Note: The measures of tree variables are undertaken immediately prior to thinning.

3.2.2 SilviScan and NIR data collection

One 12 mm radial wood core was obtained from each of 35 trees at Creekton, 21 trees at Goulds and 52 trees at Lisle. Cores were used to collect NIR spectra radially from the pith to the cambium by Medhurst *et al.* (2012), and then a strip cut lengthwise which was used to obtain the radial variation in wood properties with SilviScan. In brief, cores were extracted at breast height (1.3 m) in a north-south direction using a Trecor™ (CSIRO) mechanised corer, and immediately dehydrated by successive ethanol (70%, 90% and 99%) baths before being air-dried to equilibrium moisture content. Once the samples were dried, near-infrared spectra were collected at 1 mm intervals from bark to pith. Spectra were collected directly from the radial face of cores, using a custom-built scanning system (Downes *et al.* 2010a; Figure 6 b,c) attached to a Bruker MPA FT-NIR spectrometer (Bruker Optik GmbH, Ettlingen, Germany). For assessment with SilviScan, the cores were cut using a twin-blade saw into strips with dimensions of 7 mm (longitudinal) x 2 mm (tangential) x pith-to-bark core length (radial) (Downes *et al.* 2014; Medhurst *et al.* 2012). In the case of the Lisle samples, however, SilviScan data were collected on the offcuts adjacent to the strips due to excessive discoloration from the burning of the surface of strips at the time of cutting with the twin-blade saw.

SilviScan-3 was used to simultaneously assess density, MFA and MOE_d from pith to cambium on the radial face of the strip samples. Density was obtained using an X-ray densitometer with 0.025 mm resolution and MFA with an X-ray diffractometer with 1 mm resolution. Density data were consolidated to 1 mm intervals and MOE_d was calculated indirectly using density and MFA data at the resolution of MFA data (Evans and Ilic 2001).

3.2.3 NIR calibration model development and cross validation

Radial NIR calibration models were developed for density, MFA and MOE_d from SilviScan measurements of these traits using all 1 mm increment observations previously collected by Medhurst *et al.* (2012). Twenty-four cores (1, 2 and 21 from Creekton, Goulds and Lisle, respectively) were excluded from NIR calibrations model development due to poor alignment between NIR spectra and SilviScan readings,

which would have produced errors at the point-level when generating calibrations. In total, 34, 19 and 33 cores from Creekton, Goulds and Lisle were used in this study. Three different data sets were used in the NIR calibration, combining two sites per set (Table 3.2). In other words, the first set was from sites Creekton and Lisle (Creekton-Lisle), the second set was from sites Goulds and Creekton (Goulds-Creekton), and the last set was from sites Lisle and Goulds (Lisle-Goulds) (Table 3.2). This was done as the application of these models to resource characterisation required predicting density, MFA and MOE_d values from independent sites not included in the NIR model development.

Table 3.2 The number of points used in model development and the mean, standard deviation (SD), minimum (Min) and maximum (Max) of the SilviScan point values.

Wood property	Calibration site	Observations	Mean	SD	Min	Max
Density (kg m ⁻³)	Creekton-Lisle	7510	605.3	146.4	293.8	1178.1
	Goulds-Creekton	6106	582.3	151.1	283.8	1157.9
	Lisle-Goulds	6308	632.3	155.5	283.8	1178.1
MFA (degrees)	Creekton-Lisle	7510	15.8	5.1	0.3	34.0
	Goulds-Creekton	6106	14.8	4.7	0.3	67.3
	Lisle-Goulds	6308	16.9	4.3	7.0	67.3
MOE _d (GPa)	Creekton-Lisle	7510	12.9	4.8	2.0	37.9
	Goulds-Creekton	6106	13.4	5.0	1.7	37.9
	Lisle-Goulds	6308	13.1	4.5	1.7	28.6

Calibration models were developed using partial least square (PLS) regression analyses undertaken using 'Bruker Quant' of the OPUS 5.5 software package. Four pre-processing methods were examined in an effort to optimise the calibrations, through elimination or minimisation of variability in the spectra unrelated to the property of interest (Bruker 2006 3005). Four pre-processing methods were examined in an effort to optimise the calibrations: i) no spectral pre-processing, ii) 1st derivate, iii) 2nd derivate and iv) minimum-maximum normalization. The first derivative pre-processing involved calculation of the first derivative of the spectrum. In this case, steep edges of a peak become more important compared to flat regions. This method is mainly used to emphasize pronounced, but small

features over a broad background. The second derivative pre-processing is similar to the first derivative, but it allows evaluation of extremely flat regions. The minimum-maximum normalization, first subtracts a linear offset and then sets the y-maximum to a value of 2 by multiplication with a constant.

Obvious outliers were eliminated manually based on the differences between observed and predicted values. Accordingly from zero to 20 outliers were eliminated depending upon the pre-treatment applied, which reflected an average loss of 0.4% of total data used to develop the calibrations.

The reliability of calibration models was assessed using cross validation with one sample excluded from the data set (Downes *et al.* 2009b; Naes *et al.* 2002; Schimleck *et al.* 2006). For each calibration set, wood property and pre-processing method, the optimal calibration model was selected based on multiple criteria including maximising the coefficient of determination (R^2), minimising the root mean square error of cross validation (RMSECV), and minimising the rank (the number of vectors of partial least squares required) (Downes *et al.* 2007; Downes *et al.* 1997).

3.2.4 Validation of selected calibration models across sites

Each of the three calibration models were used to predict density, MFA and MOE_d values in one of three independent validation sets. In each case the validation set came from the site that was not used in the development of the calibration models, e.g. Creekton data were the validation set for the Goulds-Lisle calibration model (Table 3.3).

Regression analyses were then undertaken to determine the extent to which NIR predicted data explained variation in SilviScan-measured (i.e. reference) data. These regression analyses were undertaken at two levels - point-level and tree-level. The first level was the 1 mm point averages from the radial scans, and the second was the tree weighted means. The tree weighted means were estimated by weighting each point by the total area it represented in a breast height disk based on its radial position from the pith, to allow a more accurate representation of the tree-level

wood property means (Downes *et al.* 1997). This methodology assumed rings were circular and that there was no pith eccentricity.

Regression analyses were conducted using the *lm* function of R (R Core Team 2015). To evaluate the precision and accuracy of validations the coefficient of determination (R^2), root mean square error of prediction (RMSEP), standard error of prediction (SEP) and bias (BIAS), which is defined here as the average difference between SilviScan and NIR-prediction were calculated according to (Naes *et al.* 2002) as given below:

root mean square error of prediction was defined as

$$RMSEP = \sqrt{\sum_{i=1}^{N_p} (\hat{y}_i - y_i)^2 / N_p}$$

; standard error of prediction was achieved by

$$SEP = \sqrt{\sum_{i=1}^{N_p} (\hat{y}_i - y_i - BIAS)^2 / (N_p - 1)}$$

and bias was calculated by

$$BIAS = \sum_{i=1}^{N_p} (\hat{y}_i - y_i) / N_p$$

where “ \hat{y}_i ” and “ y_i ” are the NIR-predicted and SilviScan (measured reference) values for the samples, respectively, and “ N_p ” is the number of samples in the study.

Table 3.3 The number of points and trees in the validation data set and the unweighted mean, standard deviation (SD), minimum (Min) and maximum (Max) of the SilviScan point values.

Wood property	Validation set	Level	Observations	Mean	SD	Min	Max
Density (kg m ⁻³)	Creekton	Point	3654	555.4	142	293.8	1073.1
		Tree	34	581.1	52.1	469.6	693.3
	Goulds	Point	2452	609.3	160.3	283.8	1157.9
		Tree	19	656.8	35.2	567.5	718.8
	Lisle	Point	3856	655.3	150.8	322.6	1178.1
		Tree	33	691.8	56.4	554.3	773.0
MFA (degrees)	Creekton	Point	3654	13.7	5.5	0.3	32.4
		Tree	34	11.9	2.6	7.5	18.3
	Goulds	Point	2452	15.9	3.8	8.5	67.3
		Tree	19	14.7	1.3	12.5	17.3
	Lisle	Point	3856	17.9	4.7	7	34
		Tree	33	16.7	2.3	11.6	21.0
MOE _d (GPa)	Creekton	Point	3654	13.1	5.3	3.4	37.9
		Tree	34	14.5	2.2	10.1	21.0
	Goulds	Point	2452	13.6	4.7	1.7	28.6
		Tree	19	15.2	1.2	13.1	17.0
	Lisle	Point	3856	12.7	4.3	2	26
		Tree	33	14.1	1.6	11.1	16.8

3.2.5 Analysis of slope and intercept of MOE_d

As MOE_d is a crucial physical wood property for structural products such as plywood, an exploratory test was conducted to determine the ability of the NIR calibrations to predict pith to cambium trends within trees. In order to do this, simple linear regression models were fitted for each tree; the pith to cambium MOE_d weighted by radius values (SilviScan and NIR predicted) was defined as the response variable and distance from pith as the independent variable. The slope and intercept of each regression were then compared among sites with one-way ANOVA (R Core Team 2015) to determine if there were significant differences among sites in the intercept and slope. This was a first attempt at the modelling of the radial change in MOE_d which is undertaken in greater detail in Chapter 4.

3.2.6 Testing of the NIR model developed for *E. globulus*

As the NIR model previously developed by Forest Quality Pty Ltd. for *E. globulus* to predict SilviScan density, MFA and MOE_d was available (Downes *et al.* 2014), this was also used to predict values for the *E. nitens* samples from the three sites. The fit of these NIR predictions to the SilviScan data was assessed using the same parameters as described above (R^2 , RMSEP, SEP, BIAS). Because *E. globulus* and *E. nitens* are relatively closely related, and both the *E. nitens* and *E. globulus* models were developed for Australian-grown plantation material, it was thought justified to explore the possibility that this *E. globulus* may be relevant to the current *E. nitens* material.

3.3 Results

3.3.1 Calibrations

Pre-processing was not crucial to improve the cross validation coefficient of determination (R^2) for the majority of traits or sites. In fact, when pre-processing was applied, the coefficient of determination decreased and the RMSECV increased in the majority of cases (Table 3.4). For example, the R^2 of the calibration model for MOE_d from Lisle-Goulds was 79.7% without pre-processing but 78.9%, 63.8% and 73.2% with 1st derivate, 2nd derivate and minimum–maximum normalization, respectively. Similarly the RMSECV was 100 without pre-processing and increased to 102, 143 and 122 with the respective pre-processing options. Of the three pre-processing options tested, the 1st derivate was generally the best and the 2nd derivate the worst in terms of R^2 and RMSECV. However, while generally better R^2 and RMSECV were obtained without pre-processing, this was generally only achieved at the expense of an increase in model rank. This was most evident for MFA and MOE_d. For example with MOE_d, there was generally slightly higher R^2 and slightly lower RMSECV values with no pre-processing compared with the 1st derivate pre-processing, but this required a nearly two-fold increase in model rank. Accordingly, for all three traits the 1st derivate pre-processing was chosen for predicting NIR predicted wood properties of independent sites (validation sets) as it

had lower model rank than no pre-processing, yet only marginally lower coefficient of determination and marginally higher RMSECV.

Table 3.4 Cross-validation statistics for wood properties of the calibrations sets derived from pairwise combinations of the study sites and using point-level data

Wood property	Pre-processing	Creekton-Lisle		Goulds-Creekton		Lisle-Goulds	
		R ² (Rank)	RMSECV	R ² (Rank)	RMSECV	R ² (Rank)	RMSECV
Density (kg m ⁻³)	None	76.5 (6)	98.4	77.5 (6)	93.4	74.5 (7)	100.0
	1 st derivate	73.2 (5)	105.0	75.1 (4)	98.4	73.8 (6)	102.0
	2 nd derivate	61.3 (3)	126.0	57.1 (4)	129	48.7 (3)	143.0
	Min max normalization	73.0 (6)	105.0	72.4 (3)	104	62.6 (4)	122.0
MFA (degrees)	None	72.1 (9)	3.8	70.1 (7)	3.83	63.9 (7)	3.5
	1 st derivate	67.1 (4)	4.1	71.1 (4)	3.77	61.1 (4)	3.6
	2 nd derivate	63.1 (3)	4.3	61.5 (3)	4.35	54.5 (3)	3.9
	Min max normalization	68.4 (5)	4.0	69.0 (6)	3.9	59.1 (4)	3.7
MOE _d (GPa)	None	84.6 (6)	3.3	84.2 (7)	3.36	79.7 (7)	3.3
	1 st derivate	83.3 (5)	3.5	83.2 (4)	3.46	78.9 (5)	3.4
	2 nd derivate	76.2 (3)	4.1	72.5 (4)	4.43	63.8 (3)	4.4
	Min max normalization	83.8 (6)	3.4	80.4 (5)	3.74	72.9 (6)	3.8

Rank: Number of vectors of partial least squares

R²: Coefficient of determination

RMSECV: Root mean square error of cross validation

3.3.2 Predictions

The results from applying the models developed from the various pairwise combinations of sites to predict the wood properties of the third site (validation set) are shown in Table 3.5. Predictions for the independent validation sets explained a lower proportion of variation in wood properties than the comparable cross-validation models developed with the 1st derivate pre-processing shown in Table 3.4. At the 1 mm point level (i.e. precision of 1 mm) for example, when the Creekton-Lisle model for MFA was applied to NIR spectra from Goulds the model explained (R²) only 38.9% of variation in SilviScan MFA. The best R² for prediction occurred in MOE_d at Creekton using the Lisle-Goulds model, but this was still poor (R²<65%). Examples of the prediction for Creekton at the point- and tree-level are shown in Figure 3.5.

Table 3.5 Point- and tree-level statistics of wood properties for each *E. nitens* independent validation data set for density, microfibril angle and modulus of elasticity.

Wood property	Calibration set	Validation set	Pre-processing	Level	Prediction (R ²)	RMSEP	SEP	Bias
Density (kg m ⁻³)	Lisle-Goulds	Creekton	1 st derivate	Point	54.0	132.2	104.9	80.4
				Tree	5.27	91.4	49.1	77.1
	Creekton-Lisle	Goulds	1 st derivate	Point	50.5	116.2	114.2	-21.6
				Tree	13.1	50.2	42.01	-27.5
	Goulds-Creekton	Lisle	1 st derivate	Point	44.9	174.1	126.6	-119.6
				Tree	24.2	138.1	65.3	-121.7
MFA (degrees)	Lisle-Goulds	Creekton	1 st derivate	Point	45.9	4.73	4.1	2.4
				Tree	25.6	4.75	2.3	4.2
	Creekton-Lisle	Goulds	1 st derivate	Point	38.9	3.21	3.0	-1.1
				Tree	1.8	1.88	1.7	-0.9
	Goulds-Creekton	Lisle	1 st derivate	Point	30.0	6.78	4.3	-5.2
				Tree	0.1	5.79	2.5	-5.2
MOE _d (GPa)	Lisle-Goulds	Creekton	1 st derivate	Point	64.0	4.01	3.3	2.3
				Tree	55.5	2.54	1.9	1.7
	Creekton-Lisle	Goulds	1 st derivate	Point	51.9	3.55	3.6	-0.2
				Tree	53.7	1.38	1.3	-0.6
	Goulds-Creekton	Lisle	1 st derivate	Point	57.0	4.14	3.6	-2.1
				Tree	5.9	2.81	2.0	-2.0

R²: Coefficient of determination

RMSEP: Root mean square error of prediction

SEP: Standard error of prediction

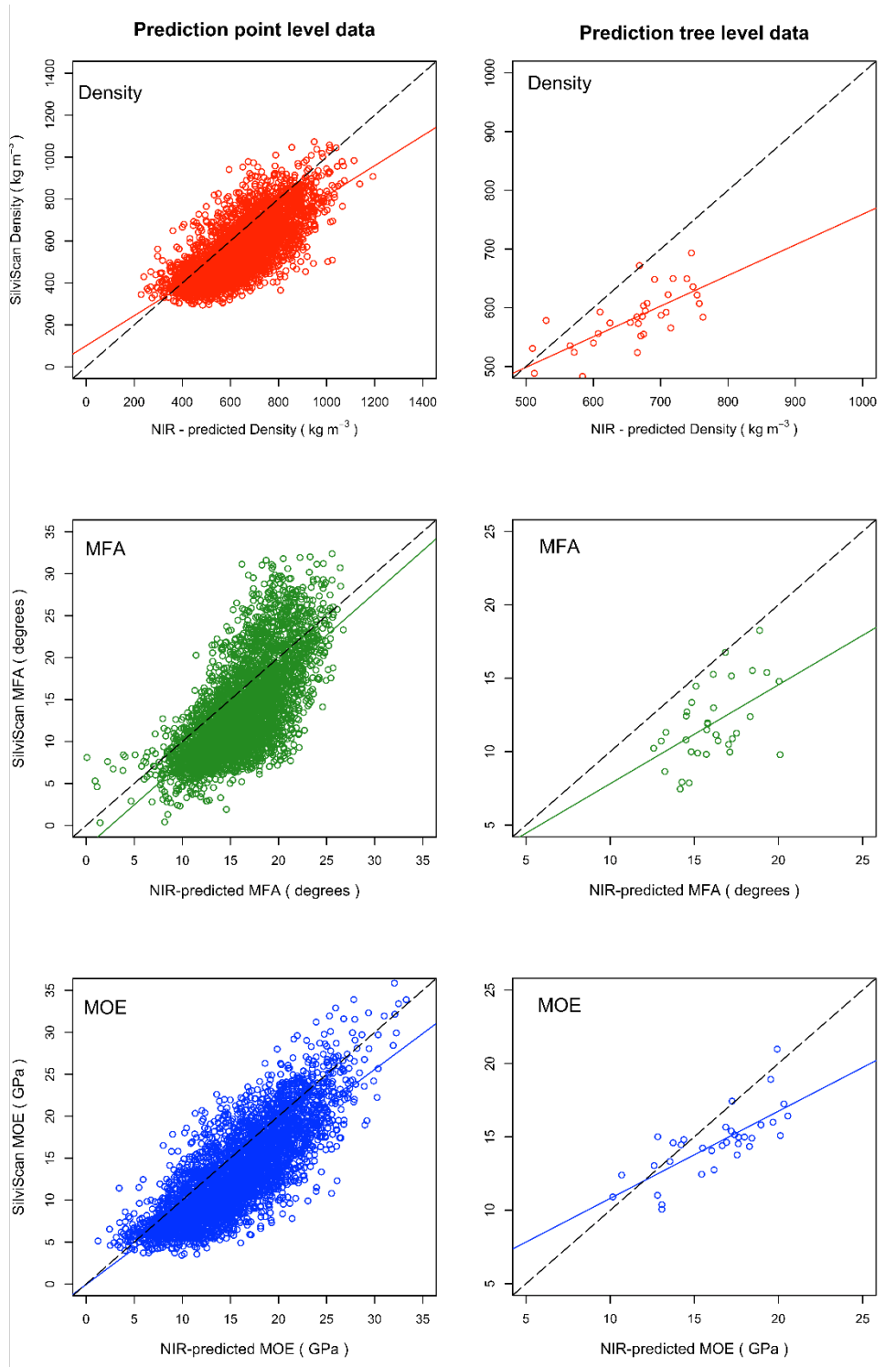


Figure 3.1 Point-level (left) and tree-level (right) predictions for the Creekton site based on the Lisle-Goulds near infrared reflectance (NIR) model for density, microfibril angle (MFA) and dynamic modulus of elasticity (MOE_d). The SilviScan measurements are plotted against the NIR predicted values. The dashed line represents a 1:1 relationship and the solid line shows the fitted linear regression (R^2 values are given in Table 3.5).

3.3.3 Analysis of slope and intercept of MOE_d

Overall the pattern of radial change in MOE_d within trees was similarly predicted by the SilviScan and NIR data (Figure 3.2), with most trees showing a trend for increasing MOE_d from pith to cambium at the three sites. The relation between SilviScan and NIR predicted slopes (Figure 3.2) shows that precision of the prediction at Creekton and Lisle was very good, but for Goulds there was some bias. However, there were no significant differences in the slope of radial change among sites using either the SilviScan data (radial position by site interaction $F_{2,83}=3.1$, $P=0.051$) or NIR predictions ($F_{2,83}=2.2$, $P=0.119$). On the other hand, while tree area-weighted means evaluated by SilviScan did not show significant differences among sites ($F_{2,83}=2.44$, $P=0.094$), highly significant differences were detected in NIR predicted means ($F_{2,83}=25.6$, $P<0.001$).

In general, the pith-to-bark slopes were satisfactorily predicted by NIR calibration models when applied to independent sites (Figure 3.2) but the predictions of tree means were biased and often poorly predicted (Table 3.5). This is illustrated by the two examples shown Figure 3.3. In the case of tree 907007 (Goulds site) the slope of the radial change in MOE_d is similar for the NIR predicted and SilviScan, but the R^2 for the 1 mm point-level data is poor and the mean (and intercept) is systematically over-estimated across the radial profile. In contrast, in tree 1009033 (Creekton site) the prediction has a reasonably good accuracy and precision throughout the radial profile.

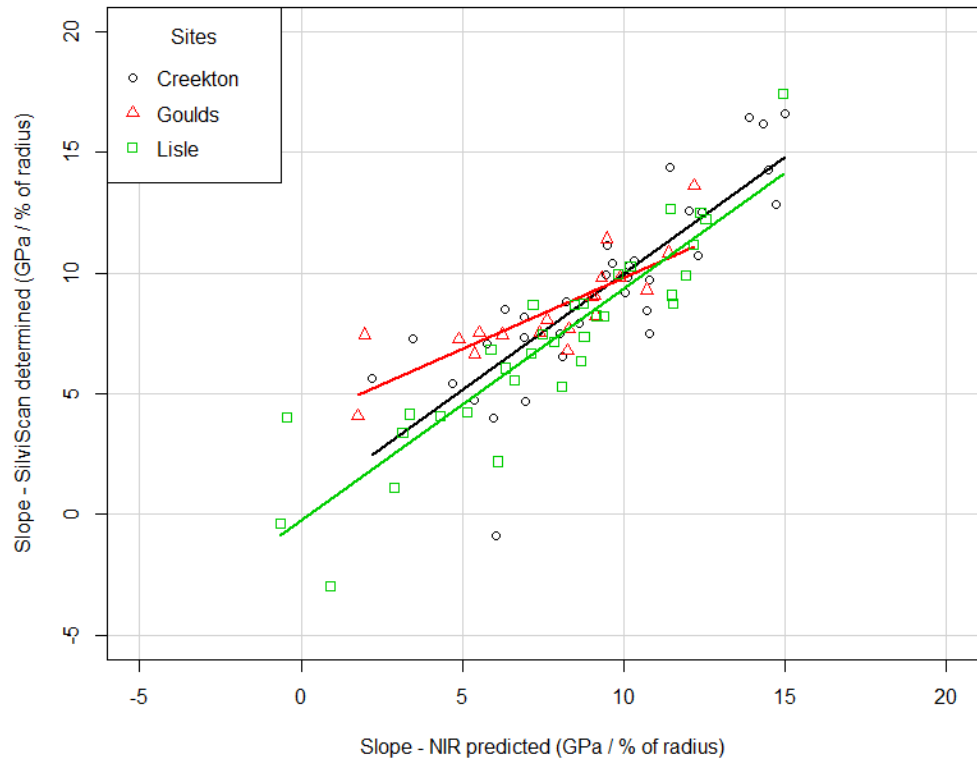


Figure 3.2 Slope of the radial change in MOE_d from pith to cambium estimated from linear regression using the SilviScan data plotted against the slope estimated from the NIR predictions for trees from Creekton ($n=34$), Goulds ($n=19$) and Lisle ($n=33$).

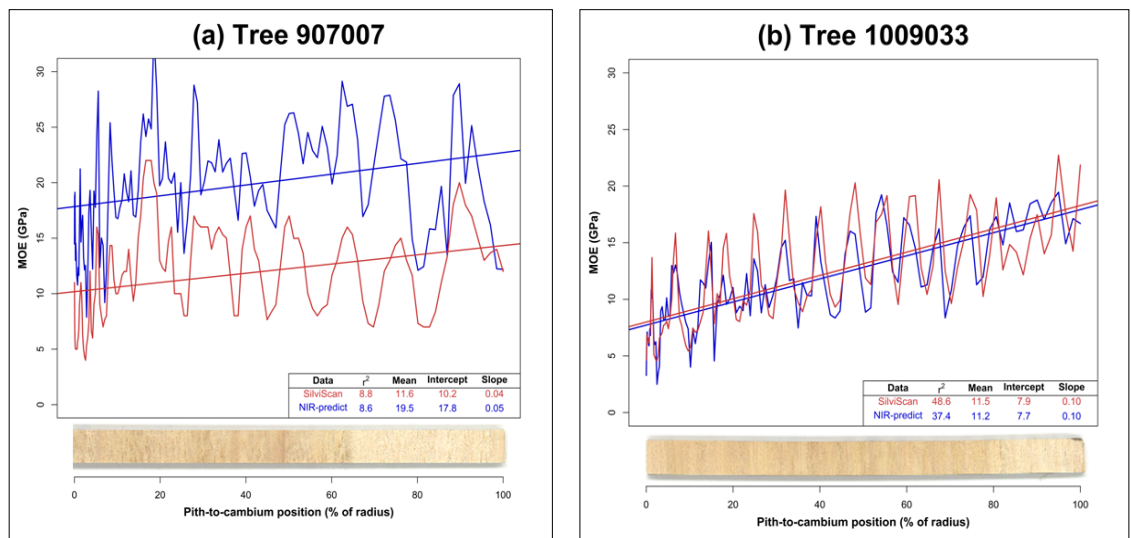


Figure 3.3 SilviScan (red line) and NIR predictions (blue line) using point-level data and their slopes from simple linear regression, for individual trees from a) Goulds and b) Creekton. The SilviScan and NIR data were obtained from the core pictured

3.3.4 Predictions using the NIR model developed for *E. globulus*

Using the *E. globulus* model developed by Forest Quality Pty Ltd. for *E. globulus*, the R^2 of prediction for the *E. nitens* sites was higher in 12 of the 18 cases than those obtained using the *E. nitens* models (Table 3.6).. With the *E. globulus* model, the R^2 from the tree-level predictions for MFA and MOE_d were less variable and slightly higher for the problematic Lisle site (R^2 7-19.3%) than obtained with the *E. nitens* models (R^2 0.1 to 5.9%)(Table 3.5). However, the tree-level data for Goulds were still poorly predicted (R^2 11.5 to 20.9%) for all traits, making this model also unreliable for resource characterisation in *E. nitens*.

Table 3.6 Cross-validation statistics of *E. globulus* calibrations and predictive statistics for point- and tree-level SilviScan data for wood properties in the three *E. nitens* study sites.

Wood property	Calibration set		Validation set					
	R^2 (Rank)	RMSECV	Site	Level	Prediction (R^2)	RMSEP	SEP	Bias
Density (kg m ⁻³)	76.3 (10)	49.1	Creekton	Point	63.3	89.6	88.5	-14.4
				Tree	62.9	39.5	31.2	-24.1
			Goulds	Point	55.5	109.2	108.2	-14.6
				Tree	16.7	59.0	50.0	-31.3
			Lisle	Point	37.6	128.4	128.4	-1.5
				Tree	19.1	79.1	77.0	-18.0
MFA (degrees)	62.4 (7)	2.34	Creekton	Point	47.7	4.3	4.1	-1.4
				Tree	36.8	2.1	2.1	-0.4
			Goulds	Point	38.4	3.8	3.1	-2.1
				Tree	11.5	2.2	1.5	-1.6
			Lisle	Point	36.9	6.6	3.8	-5.4
				Tree	7.0	5.6	2.3	-5.1
MOE_d (GPa)	80.3 (9)	2.1	Creekton	Point	68.9	3.0	3.0	-0.1
				Tree	76.9	1.1	1.1	-0.3
			Goulds	Point	54.8	3.3	3.2	-0.6
				Tree	20.9	1.6	1.3	-1.0
			Lisle	Point	63.4	3.4	2.7	1.9
				Tree	19.3	2.4	1.5	1.9

R^2 : Coefficient of determination; (Rank): Number of vectors of partial least squares

RMSCV: Root mean square error of cross validation

RMSEP: Root mean square error of prediction

SEP: Standard error of prediction

3.4 Discussion

NIR calibration models for density, MFA and MOE_d for *E. nitens* were successfully developed in this study, but the capacity of these models to predict wood properties when applied to independent sites was mixed and generally poor. Although NIR models developed in previous studies on *E. globulus* performed better than models developed in this study, they were still not capable of satisfactorily predicting wood properties of *E. nitens*.

In the case of the selected calibrations (1st derivative pre-processing), the variance explained by the coefficient of determination for cross-validation was similar to other NIR calibrations developed for eucalypt species. For density, however the coefficients of determination of the models developed in the current study (from 73.2 to 75.1%) are lower than that reported in Schimleck *et al.* (2006) for the same species ($R^2=93\%$), but higher than that reported ($R^2=67\%$) for *E. globulus* (Wentzel-Vietheer 2012). Schimleck *et al.* (2006) developed models from spectra and wood property measurements averaged over 5 mm sample lengths, as opposed to 1 mm sample lengths in the current study, which may, in part, explain the difference in coefficients of determination. The MFA calibrations at the 1 mm point level had moderate coefficients of determination (from 61.1 to 71.1%), in the same range as that observed in a previous study of *E. nitens* ($R^2=69\%$) (Schimleck *et al.* 2006) and slightly higher than observed in *E. globulus* (57.6%) (Wentzel-Vietheer 2012). In the case of MOE_d (1 mm point level), for the three sets of calibrations the coefficients of determination (from 78.9 to 83.5%) were comparable with those reported by Schimleck *et al.* (2006) in the same species.

The prediction of wood properties applying NIR calibrations to independent sites showed predictions with lower coefficients of determination and larger RMSE than calibration models in virtually all cases. A similar situation was found by Schimleck *et al.* (2006) when evaluating *E. nitens* in solid wood samples. Schimleck *et al.* (2006) obtained coefficients of determination in the independent site predictions for density of $R^2=89\%$, MFA of $R^2=20\%$ and MOE_d of $R^2=66\%$. In the present case the

best point-level predictions for density and MOE_d had lower R^2 with 54% and 64%, respectively, and for MFA a larger R^2 of 46%.

From a prediction point of view the analysis was focused on the coefficient of determination because it denotes the precision of the prediction (Downes 2011). The results showed that the NIR model developed cannot be relied on to accurately predict density, MFA or MOE_d for trees from independent sites, with the tree-level R^2 ranging from 0% to a maximum of only 56%. There was a notable drop in the percentage of variation explained by the NIR model from cross-validation within the calibration data set to prediction at an independent site. In addition, the drop off in R^2 between point- and tree-level data was generally substantial, with the exception of the prediction of the Goulds MOE_d . The lower levels of the variance explained in tree-level data from independent sites suggest that NIR predicted data is not suitable for ranking or determination of differences between sites. This was clearly apparent in the MOE_d predictions where NIR predictions gave different results to the SilviScan data when evaluating the differences among sites based on area-weighted tree mean predictions.

The other criteria to consider in the evaluation of the predictive capacity of the NIR models is accuracy, which refers to the closeness of the predicted values to the true values, and is evaluated for either validations or predictions by RMSEP (Naes *et al.* 2002). Although the R^2 values are not particularly low, the values of RMSEP are higher in comparison with results from *E. globulus* calibrations (Downes *et al.* 2014) using the same methodology. In addition, the issue of accuracy is reflected in the prediction of MOE_d from the NIR model. Despite the NIR predicted values giving a reasonable prediction of the radial trends in MOE_d , they failed in the accuracy of prediction of the individual points through the radial profile as well as the area-weighted tree means.

Downes (2011) and Wentzel-Vietheer *et al.* (2013) discuss several factors which could lead to lack of accuracy in NIR calibrations derived from radial scans, which may be relevant to the present study. Firstly, there may be poor alignment between SilviScan and NIR spectra along the radial profile. There could be minor (< 1 mm)

misalignment in the starting point of the two scans. Furthermore, while the alignment was undertaken carefully, it was not possible to avoid the situation that the SilviScan measures were not made in the same samples in the case of Lisle. Developing different approaches to averaging the radial profile might increase the accuracy of the NIR model. For example, models based on average results over 5~10 mm sample lengths, rather than 1 mm sample lengths could reduce the problem of misalignment of NIR and SilviScan data along the radial profile. Downes *et al.* (2012) and Downes *et al.* (2010a) have achieved successful results for cellulose using surface scanning at 10 mm increments. Secondly, although SilviScan and NIR data was averaged to 1 mm increments, differences in the resolution of the SilviScan and NIR scans could cause inaccuracies. Finally, reduced accuracy could arise from the different parts of the wood strip being assessed by NIR and SilviScan. The NIR reflectance spectra are collected from the radial–longitudinal surface whereas the SilviScan data is generated from X-rays transmitted through the 2 mm tangential thickness of the strip. Micro-scale measurement error may thus arise from the perspective of the NIR spectra if orientation of density variation caused by the annual cycle of early/late wood, associated with growth rings, is not perfectly tangential (Wentzel-Vietheer *et al.* 2013).

There are several ways the precision of NIR predictions may be improved by different sampling strategies. Firstly, the expansion of the calibration data set to include more sites may be a way of producing a model which is more robust and able to better predict values for independent sites. This approach has certainly been successful in the case of wood chemical properties such as pulp yield where multi-site, multi-species ‘global’ models have been developed (Downes *et al.* 2010b). In spite of including two of the three different sites in the developed of calibrations in a pairwise manner, the sites were similar in genetic background and silviculture treatments. They did vary in rainfall (776-1086 mm) which could be important given that water availability is known to affect density in *Eucalyptus* (Wimmer *et al.* 2002a; Wimmer *et al.* 2002b). However, while there was considerable point- and tree-level variation in wood properties, the site means were not markedly different as observed from their basic statistics. The absence of marked differences between

sites may explain the better performance of the previously developed *E. globulus* model compared with the current *E. nitens* model. The *E. globulus* model was developed using trees from three sites which differed markedly in their annual rainfall (620-1100mm), evaporation and soil water-holding capacity (Downes *et al.* 2014). Consequently, future NIR model development should consider the inclusion of sites with greater contrast in silviculture and environmental growth conditions and thus an increased range of wood property values, however, this could be time consuming and expensive (Downes 2011). Secondly, stratified samples could be used to improve precision. The extreme values of wood properties, especially MFA and MOE_d, are not well represented in the models. Using stratified sampling of spectra and SilviScan to build model calibrations may give more balanced and accurate predictions.

In conclusion, neither *E. nitens* nor *E. globulus* MOE_d calibrations generated satisfactory predictions of point- and tree-level data, with a big R² range (19.3 to 76.9) that diminished the precision or accuracy of these models, albeit *E. globulus* generally performed better in terms of R² for the wood properties. Consequently, the present NIR models developed here do not achieve the study aim to develop calibration models that can predict density, MFA and MOE_d with precision and accuracy that could be used to characterise *E. nitens* plantations at a regional scale (Tasmania).

Chapter 4 The influence of site on the radial variation in modulus of elasticity, microfibril angle and density of veneer logs from plantation-grown *Eucalyptus nitens*

4.1 Introduction

4.1.1 General trends of density, microfibril angle and modulus of elasticity

In forest trees, wood properties, such as density, microfibril angle (MFA) and modulus of elasticity (MOE), vary systematically in the stem from pith to cambium with direct implications for the processing and utilisation of wood. In general, wood density shows a gradual increase from the pith to the cambium in forest trees (Auty *et al.* 2014; Burdon *et al.* 2004; Mansfield *et al.* 2009; Xiang *et al.* 2014), including eucalypts (Harwood *et al.* 2005b; Medhurst *et al.* 2012). In eucalypts, as in other trees, MFA decreases non-linearly from pith to cambium, with a rapid drop near the pith followed by a more gradual decrease towards the cambium (Forrester *et al.* 2013; Medhurst *et al.* 2012). In contrast, MOE increases non-linearly from pith to cambium, initially with a steep rate of increase near the pith followed by a slower rate of increase towards the cambium (Harwood *et al.* 2005a; Harwood *et al.* 2005b; Leban and Haines 1999).

The radial variation in wood properties is consistent with differences in wood properties between juvenile (also called ‘corewood’) and mature (also called ‘outerwood’) wood observed in many tree species, which is particularly marked in conifers (Burdon *et al.* 2004; Lachenbruch *et al.* 2011; Mansfield *et al.* 2009; Zobel and van Buijtenen 1989a). While the concepts of juvenile/mature and core/outer wood interchangeably in the literature and is the case herein, Burdon *et al.* (2004) do propose they be restricted describe the vertical and radial changes, respectively in wood properties within a tree. In a radial direction, the differences between juvenile and mature wood is usually based on anatomical features, such as MFA, vessel length, cell diameter and wall thickness (Giroud *et al.* 2015; Maeglin 1987;

Mansfield *et al.* 2009) Despite this radial variation in many wood properties, there is no definitive or universally accepted boundary between core and mature wood. This is because the radial change is often gradual, its nature may depend on the wood property and species in question, and the change varies depending on the methodology used to determine the point of transition (Giroud *et al.* 2015). This difference between juvenile and mature wood is also more obvious in larger and/or older trees than smaller and/or younger trees (Lachenbruch *et al.* 2011). The mature wood is usually delineated as the point when the wood property evaluated reaches a relatively stable value (i.e. approaches an asymptote), and the section between juvenile and mature wood has been termed ‘transition wood’ (Giroud *et al.* 2015). However, the magnitude of the difference between juvenile and mature wood, the rate of transition and the proportion of transition age wood within a trunk depend on environmental, silvicultural and genetic factors (Maeglin 1987).

The importance of pith-to-cambium heterogeneity in wood properties depends on the targeted end-product. In the case of engineered wood products, such as plywood and LVL, threshold minimum values in mechanical wood properties are defined by industry standards or by end-users. The ability to estimate the proportion of veneer from a log, tree or stand would help optimize the use of raw material, thus affecting the final cost of products, value of logs and ultimately the forest value (Lachenbruch *et al.* 2011; McGavin *et al.* 2014a; West 2014; Zhao *et al.* 2007).

4.1.2 Modelling radial variation

A detailed understanding and ability to model radial variation in wood properties would allow growers and processors to optimise the value of the product and/or profit from forest resources (Bao *et al.* 2001). Such models are particularly pertinent for the rotary veneering process. While predictions of average wood properties for a tree give only general information about potential veneer recovery of a given quality, radial profile models permit more accurate estimation of potential veneer recovery by, for example, estimating the volume of veneers with a specific mechanical grading (Leban and Haines 1999; Moore *et al.* 2014). Ideally models of

the radial profile of trees could be used to quantify and predict the variation of wood properties at multiple scales, such as among logs, trees and stands. Early attempts to formally model this radial variation have been overviewed by Burdon *et al.* (2004). Such attempts focused mainly on softwoods, such as *Pinus radiata*, where the radial variation tends to be asymptotic for many key wood properties. In such cases, the key parameters describe in non-linear models include the intercept (first ring) and asymptote, the shape of the curve, and the rate of approaching the asymptote. Such models would permit the characterisation of the forest resource and segregation of the resource according to specific end product requirements (Burkhart and Tomé 2012; Tian and Cown 1997a; Tian and Cown 1997b; Walker 2006; Wang and Dai 2013).

4.1.3 Examples of the application of models

A number of different linear and non-linear models have previously been used to explain radial trends in density, MFA and MOE. These models have been developed for a range of species like *Pinus radiata*, *P. taeda*, *Pseudotsuga menziessi*, *Quercus petrea* (Burdon *et al.* 2004; Sattler *et al.* 2014), but the majority of research in this field has focused on conifers as summarised by Zobel and Buijtenen (1989a). In eucalypts, radial variation in density has been modelled using linear (Downes *et al.* 2014) and non-linear (McGavin *et al.* 2015) models. There are few examples of models for MFA radial change in the eucalypts. Downes *et al.* (2014) and Lima *et al.* (2014) both used linear models. In conifers, on the other hand, a modified logistic function was used by Jordan *et al.* (2005) and Moore *et al.* (2014) to predict MFA as a function of ring number from the pith. For MOE, the non-linear models in the literature for conifers are variants of the Chapman-Richards (Leban and Haines 1999), Michaelis–Menten (Auty and Achim 2008) and the Mitscherlich (Briggs 1925) equations. The effect of growth rate (ring width) on the ring-level wood properties of conifers has also been modelled using a modified (Auty *et al.* 2013) or non-modified (Moore *et al.* 2014) Michaelis-Menten equation. In contrast, in *Eucalyptus* the only example of a non-linear model found in the literature for MOE_d used a sigmoidal function (McGavin *et al.* 2015).

4.1.4 Cambial age or tree size?

In the development of radial models it is important to consider the metric of the radial axis, which may be cambial age (number of years from pith, measured using tree rings), distance from pith or area from pith (measured in distance and converted to percent of cross-sectional area) (Sattler *et al.* 2014). Cambial age is the most common metric used in radial modelling (Auty and Achim 2008; Auty *et al.* 2013; Leban and Haines 1999 3543; Lenz *et al.* 2010b; Xiang *et al.* 2014), and it has the big advantage that models so developed can be linked to growth and yield models (Mendoza and Vanclay 2008) enabling different scenarios, such as increasing rotation length and thinning intensity, to be investigated. However, this metric has practical limitations. For example, cambial age can be difficult to establish where the age of trees is unknown or within an uneven-aged forest. In addition some species, such as eucalypts, produce false rings that make it difficult to visually identify the true seasonal rings (Hudson *et al.* 1998).

When tree size (evaluated as the area from pith or distance from pith) and cambial age are compared in modelling radial change in wood properties, mixed results are obtained. Sattler *et al.* (2014) found that cambial age provided a better fit than distance from pith in *Populus* sp. and *Picea* sp. On the other hand, Kojima *et al.* (2009) found mixed results when evaluating different hardwood species with respect to fibre length, a characteristic closely related to modulus of elasticity. In *Eucalyptus*, McGavin *et al.* (2015) recommended using cambial age for increased accuracy, although practical constraints required them to use distance from pith measured from veneer ribbon in the development of their model. Indeed, the use of models based on relative distance from the pith (as opposed to age) are particularly useful to predict product quality outcomes, as in the case of their veneer processing study.

4.1.5 Aims

With interest in better characterising the Tasmanian *E. nitens* plantation resource for veneer production, the present study aimed to model radial variation in the three veneer-critical wood properties: density, microfibril angle and modulus of

elasticity, which affect mechanical grading. Data were used from three *E. nitens* plantations representing a range of environmental and silvicultural characteristics, and aimed to:

- identify models that explain the profile of radial variation in density, MFA and MOE_d with respect to cambial age and percent of cross-sectional area;
- apply these models of radial variation to quantify the extent to which the patterns of radial variation in wood properties differ among plantation sites; and
- predict the proportion of wood within harvested logs with MOE_d above a predefined threshold value used to indicate suitability for use in structural products.

4.2 Materials and methods

4.2.1 Field sites and tree selection

Three contrasting *E. nitens* plantations at Strathblane, Geeveston and Florentine in the south of Tasmania (Australia) were selected for study (Table 2.1 in Chapter 2). These sites are managed by Forestry Tasmania and were previously included in multi-species studies of veneer recovery, quality and log-end splitting (Hamilton *et al.* 2014; McGavin *et al.* 2014b; Vega *et al.* 2015). While the genetic stock involved was unknown (Vega *et al.* 2015), they encompassed different silvicultural treatments and/or site productivities. Plantations at Strathblane and Geeveston were thinned and pruned for solid wood production but differed markedly in productivity. The Florentine site was an unthinned and unpruned pulpwood stand. Within each site a measurement plot (972 to 2156 m²) was established and basal area within plots determined.

Trees for felling were then selected at random within plots, excluding trees of less than 220 or greater than 390 mm in diameter at breast height over bark (DBH; 1.3 m) or with any evident visual defects such as double leaders. The criteria of selection was developed to avoid severely suppressed trees and to meet the spindleless lathe diameter requirements to conduct recovery studies (Appendix B). At the Geeveston site, no maximum DBH criterion was applied as trees were too large and a representative sample could not be obtained within these log size constraints.

4.2.2 Preparation and sample measurement

Forty-two trees were selected in total, with twenty-one from Strathblane, ten from Geeveston and eleven from Florentine. Immediately after the felling of trees, one disk of approximately 50 mm thickness per tree was obtained from 2.5 m above ground level and stored at 5°C for seven days. Afterwards the disks were moved to a freezer (-4 °C) for a period of 3 months and while they were processed were temporarily stored in a freezer at -15°C.

Disks were planed with an electric planer before counting rings in order to improve ring boundary identification (Medhurst *et al.* 2011). A radial block sample (clear of the defects) of 20 mm x 15-20 mm x longest axis of disk was then cut from each of the disks (Figure 4.1).

These samples were dehydrated by successive ethanol baths (70%, 90 % and 100%), following the methodology described by Evans *et al.* (2000) to prevent collapse, cracking and distortion during air-dry drying (8% moisture content) and storage. From each dried block sample, one strip sample (2 mm tangentially × 8 mm longitudinally) was obtained using a twin-bladed saw for SilviScan-3™ analysis (Downes *et al.* 2014).

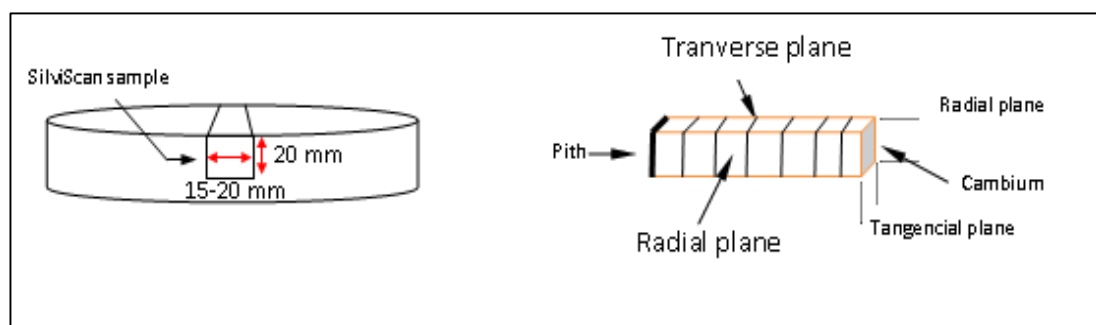


Figure 4.1 Dimensions and characteristics of the SilviScan strip sample taken from *Eucalyptus nitens* disks 2.5 m above ground-level.

The longest radial axis was sampled for practical reasons at the time of sample cutting. In hardwoods, excessive eccentricity of the pith might be associated with tension wood development, so using the longest axis in the disk could result in the inclusion of more tension wood in the samples. However, according to Washusen (2011), while tension wood has serious impact on recovery or product quality in *E. globulus*, damaging levels of tension wood appear to be less common in *E. nitens*. Visual inspection of the samples did not detected evidence of tension wood. Thus, although it is not possible to dismiss the possibility that tension wood is included in the samples taken, the chance is low. SilviScan was used to simultaneously assess density, MFA and MOE_d from pith to cambium on the radial face of the strip samples. Density was obtained using an X-ray densitometer with 0.025 mm

resolution, MFA with an X-ray diffractometer with 1 mm resolution, and MOE_d was calculated using density and MFA data at the resolution of MFA data (Evans and Ilic 2001). The SilviScan Ring Allocation (Version 2014.11.07) software package (written by Dr. Geoff Downes) in conjunction with manual ring measurements were used to define ring boundaries in each strip sample. The ring allocation software estimated the mean density, MFA and MOE_d within each ring based on the ring boundaries and wood property data inputs.

4.2.3 Data analysis

The R statistical programming environment (R Core Team 2015) was used for general statistical analysis. Analysis of non-linear models was conducted using functions of the *nlme* R package (Pinheiro *et al.* 2013). Transformation of data was deemed unnecessary as residuals appeared to be normally distributed and homocedastic.

4.2.3.1 Tree means

Unweighted means of whole-tree wood properties were estimated as the average of the ring wood property values. Additionally, tree means were estimated by weighting ring means by ring area (weighted mean), to allow a more accurate representation of the tree-level wood property means (Downes *et al.* 1997). This methodology assumed rings were circular and that there was no pith eccentricity. The methodology of Medhurst *et al.* (2011) was used to quantify eccentricity to test this assumption. Using this measure for each tree, a one-way ANOVA was used to test the differences among the study sites using the *anova* function of R (R Core Team 2015).

4.2.3.2 Differences between inner- and outer- wood

At a broad-scale the pith-to-cambium change in wood properties was investigated by comparing the inner (adjacent to the pith) and outermost (adjacent to the cambium) samples from each tree, with the difference expressed as a percentage of the innermost sample. The samples were chosen as the two innermost and two outermost rings or, following Downes *et al.* (2014), innermost and outmost 10% of

cross-sectional area. Using this tree-level data (i) a t-test was undertaken separately for each site and wood property to test the statistical significance from zero of the difference between the inner- and outermost samples, and (ii) a one-way ANOVA was undertaken to test for the difference in change among sites, with Tukey-Kramer multiple comparisons applied to compare site means. These analyses were undertaken using cambial age and percentage of area data for each wood property with the *t.test* and *anova* functions in R (R Core Team 2015).

4.2.3.3 Modelling radial trends in wood properties

Radial modelling was undertaken fitting the average wood property value for each ring as the response variable Y and i) cambial age or ii) percentage of the area from the pith as the independent variable (X). Eight linear and non-linear models were examined as a means of modelling radial trends (Table C. 3 in Appendix C). The non-linear models used were either asymptotic or sigmoidal functions. The asymptotic functions included the asymptotic exponential, asymptotic exponential with offset and Michaelis-Menten models, and the sigmoidal functions were logistic with three and four parameters, as well as Weibull and Gompertz models (Logan 2010).

The most appropriate function for each trait was selected, firstly, based on the ability to fit the model for each of the three sites separately (pooling across trees) for both cambial age and percentage of area as the independent variable, and secondly, following previous studies (Gardiner *et al.* 2011; Moore *et al.* 2014), by selecting the model with the lowest Akaike Information Criterion (AIC) values (Akaike 1974). AIC estimates the fit of each model, relative to other models. Because there is always going to be a trade-off between the goodness of fit and the number of parameters, AIC is useful because it explicitly penalizes any superfluous parameters in the candidate model (Crawley 2007). This model fitting assumed independent residuals.

Based on these preliminary analyses, density was modelled with a two-parameter linear regression function:

$$Y = a + b X$$

where ‘a’ is the intercept and ‘b’ is the slope. Microfibril angle was modelled with an asymptotic exponential model:

$$Y = \text{Asym} + (\text{R0} - \text{Asym}) * e^{-e^{\text{lrc} X}}$$

where ‘Asym’ is the right-hand-side horizontal asymptote, ‘R0’ is the Y intercept and ‘lrc’ is the natural logarithm of the rate of curvature.

Modulus of elasticity was modelled with a three-parameter logistic sigmoidal function:

$$Y = \frac{\text{Asym}}{1 + e^{\left(\frac{\text{xmid}-X}{\text{scal}}\right)}}$$

where ‘Asym’ is the right-hand-side horizontal asymptote, ‘xmid’ is the x value at half of the ‘Asym’ value (inflection point) and ‘scal’ indicates the slope at the inflection point of the curve and the left hand-hand-side horizontal asymptote is fixed at zero. Data from two trees from the Florentine site were excluded from analyses, as SilviScan-estimated trends in wood properties were clearly aberrant.

4.2.3.4 Threshold and pith value in MOE_d

With the selected MOE_d model, a threshold of 14 GPa was used to indicate the potential volume of veneer recovery for structural use. While the 14 GPa threshold refers to constructed structural plywood, we here use it as an arbitrary MOE_d threshold by which to judge individual veneer sheet quality for use in structural plywood production. As such it is probably higher than current industry targets for individual veneer sheets (D. Blackburn *pers. comm.*). It should also be noted that this threshold is based on static modulus of elasticity, whereas SilviScan values presented in this thesis refer to dynamic MOE_d, which tends to overestimate static modulus of elasticity by about 10% (Raymond *et al.* 2007).

According to the AS/NZS 2878:2000 (Australian/New Zealand Standard 2012), which describes different timber strengths for use in structural purposes, *E. nitens* is classified in strength group SD4, meaning this species has a mean modulus of elasticity of 14 GPa. For structural plywood this group is equivalent to grade F17 in AS/NZS 2269.0:2012 (2012).

Pearson correlations were calculated to establish if there was a significant relationship of the area weighted mean MOE_d of the tree with (i) the percentage of the area of the studied tree which exceeded the threshold at which the wood was potentially suitable for structural veneer (i.e. > 14 GPa) (more the better) or (ii) the cambial age at which the threshold was reached (earlier the better). These estimates would be expected to be positively and negatively correlated, respectively, with area weighted mean MOE_d .

4.2.3.5 Comparison between sites and trees in wood properties

After the selection of the appropriate models for each wood property, the selected models were fitted to data from individual trees by applying the *nlsList* function from the *nlme* package (Pinheiro *et al.* 2013) of the R language (R Core Team 2015). The parameters obtained were used to model the radial variation of wood properties within and among sites as a function of both cambial age and percentage of area.

Following the approach of Venables and Ripley (2002) and Crawley (2007), inter-site (among site) variation in model parameters was determined by one-way ANOVA tests using the individual tree parameter estimates as replication, weighted by the inverse of their standard error. This one-way ANOVA was undertaken for each combination of parameter and wood property, for both cambial age and percentage of area estimates.

Intra-site radial variation (i.e. among trees within a site) was evaluated differently. In this case the methodology described by Ritz and Streibig (2008) was used. This involved comparing the fit of a full model involving separate parameter estimates for each tree, with a reduced model, which estimates a pooled parameter for the

site. The full and reduced models for each parameter and wood property were compared using the ANOVA method implemented with the R language (R Core Team 2015).

4.3 Results

4.3.1 Tree mean values of wood properties

Based on the conventional tree means (unweighted), the differences among sites were significant for all the properties evaluated (Table 4.1). On the other hand, for the area-weighted tree means, the differences among sites were only significant for density, but where unweighted means were significantly different based on the Tukey-Kramer tests the same trends were evident (Table 4.1).

Disk eccentricity had an average of less than 10% for each site, and did not differ among these sites ($F_{2,37}=0.8$, $P>0.05$), arguing that the area-weighted means are a good estimate of the overall difference among sites.

With the area-weighted tree mean values, density was lowest at Florentine and its site mean was significantly different from Strathblane and Geeveston, according to a Tukey-Kramer multiple comparison test. Unweighted tree means were consistently lower than those based on the area weighted tree means, although Florentine was significantly less dense in both cases.

Table 4.1 Mean wood properties and significance of the differences among sites. Results are presented based on unweighted and weighted tree mean values from samples taken 2.5 m above ground level

Site	Density (kg m ⁻³)		MFA (degrees)		MOE _d (GPa)	
	Unweighted	Weighted	Unweighted	Weighted	Unweighted	Weighted
Strathblane	603.4 a	619.2 a	11.4 a	8.8 a	14.9 a	16.9 a
Geeveston	600.5 a	634.1 a	12.8 b	9.9 a	14.0 ab	16.6 a
Florentine	551.1 b	577.1 b	13.2a b	9.8 a	12.9 b	15.9 a
Significance of differences between sites						
$F_{2,37}$	5.2	4.7	4.4	2.2	3.6	1.03
P value	<0.01	0.01	<0.05	0.13	<0.05	0.38

Note: Site means that were significantly different ($P<0.05$) according to Tukey-Kramer multiple comparisons are denoted by different letters.

4.3.2 Radial variation of wood properties in the pith-to-cambium

4.3.2.1 Comparison of inner and outer wood

At each site, all wood properties exhibited a significant difference between inner- and outer-wood (t-test from zero; $P < 0.05$). The density and MOE_d of outer-wood was higher than inner-wood (10.1 to 31.7% and 91.8 to 145.9% higher, respectively, depending upon site) and MFA was lower (-55.5 to -63.1% of inner sample), regardless of whether the ring or percentage area data as used (Table 4.2). These trends were the same at all sites, but in some cases the magnitude of the change differed (Table 4.2).

Sites did not differ significantly in the magnitude of the difference in MFA between inner-wood and outer wood, and only when expressed in terms of area was there a significant difference for MOE_d ($P < 0.05$). Density showed significant differences among sites, regardless of whether age or area were used, Geeveston the greatest difference between the inner- and outer-most wood. The rank order of sites the magnitude of the change in all response variables remained the same, regardless of how the comparison was made, and whether it was significant or not. In overall wood properties, Strathblane showed the least change between pith and cambium, followed by Florentine and finally, Geeveston (Table 4.2).

Table 4.2 The site means for the difference between pith and cambium samples for density, microfibril angle (MFA) and modulus of elasticity (MOE_d). The differences were between the two innermost rings and the two outermost rings (rings) or the innermost 10% of disk area and the outermost 10% of disk area (percentage) expressed as a percentage of the innermost rings/area.

Site	Change in density (%)		Change in MFA (%)		Change in MOE_d (%)	
	Rings	Percentage	Rings	Percentage	Rings	Percentage
Strathblane	19.5 a	10.3 a	-56.9 a	-55.5 a	97.0 a	91.8 a
Geeveston	26.6 b	31.7 b	-63.1 a	-61.5 a	142.1 a	145.9 b
Florentine	10.1 ab	20.3 ab	-60.3 a	-58.2 a	137.5 a	134.0 ab

Note: Site means significantly different ($P < 0.05$) according to a Tukey-Kramer multiple comparisons test are denoted by different letters. The radial change for each wood property at each site was significantly different from zero ($P < 0.05$) according to a Student's t-test.

4.3.2.2 Models of the patterns of radial change across and within sites

4.3.2.2.1 Radial change with cambial age

The radial variation of wood properties in *E. nitens* disks varied as expected based on the comparisons above and previous studies: density and MOE_d increased and MFA decreased from pith to cambium with age (Figure 4.2 and Figure 4.3)

Density

Within sites, there were statistically significant differences in the pattern of radial change in density among trees, for both the intercept and slope of the linear model (intra-site component of Table 4.3). The exception was the low productivity site at Strathblane, where trees did not differ significantly in the rate of change in density but did in intercept (Figure 4.2 and Table 4.3). Despite the significant variation among trees within sites, sites differed significantly in intercept and slope, in a manner consistent with their previously mentioned differences in area-weighted means and magnitude of change between inner- and outer-most wood samples respectively.

The linear model fitted for density across all sites showed that the highest pith density (i.e. greatest Y intercept) was recorded at the Strathblane site, then Geeveston and finally Florentine. The highest rate of increase in density (i.e. greatest slope) was observed at Geeveston, followed by Florentine and, lastly, Strathblane (Figure 4.2 and Inter-site component of Table 4.3).

The two sites with highest rate of density increase were also the sites with higher productivity. However the lowest quality site (Strathblane), had a markedly higher intercept, indicating that density differences were established at an early age and, despite density not increasing as rapidly with age, the site still maintained second ranking in area-weighted mean density (Table 4.1).

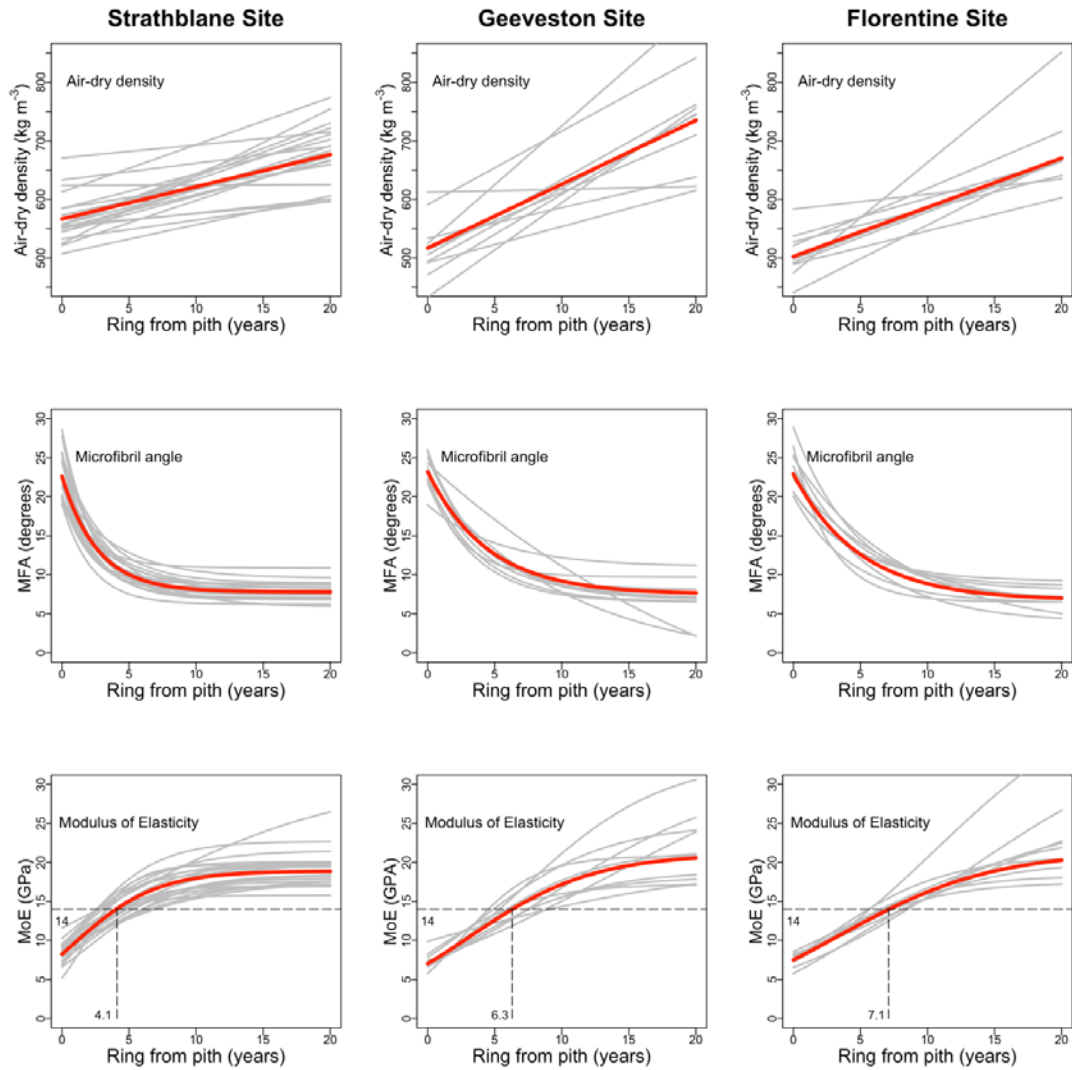


Figure 4.2 The fitted models for each tree (grey line) and site (red line) for air-dried density, microfibril angle (MFA) and modulus of elasticity (MOE_d) as a function of cambial age. The MOE_d threshold of 14 GPa is also shown along with the age at which this threshold is reached (dashed lines). Note that these models refer to wood properties measured at 2.5 m above ground level.

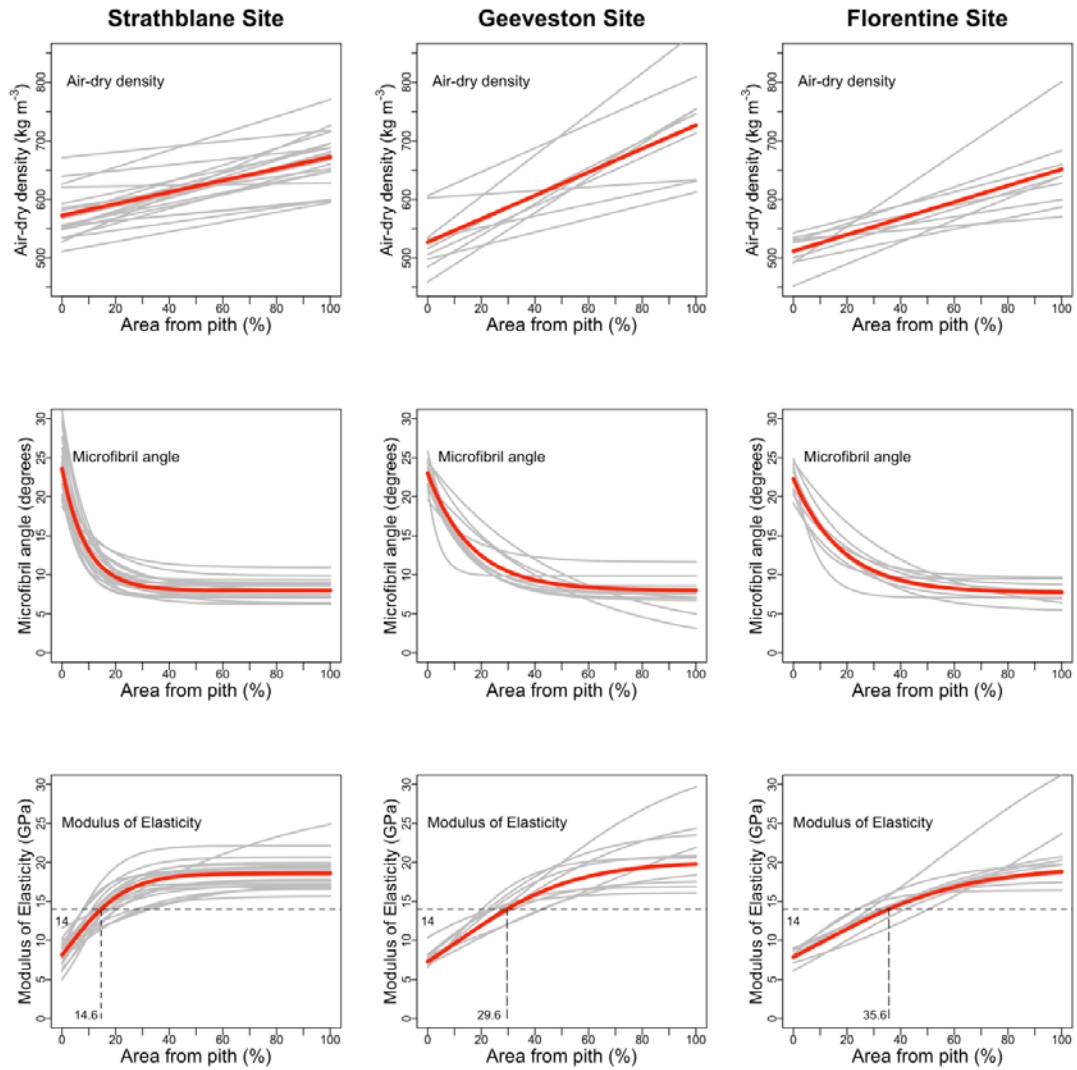


Figure 4.3 The fitted models for each tree (grey line) and site (red line) for air-dried density, microfibril angle (MFA) and modulus of elasticity (MOE_d) as a function of percent of area. The MOE_d threshold of 14 GPa is also shown along with the percent of area at which this threshold is reached (dashed lines). Note that these models refer to wood properties measured at 2.5 m above ground level.

Table 4.3 Model parameter means and standard errors (in parenthesis), F ratios and the significance of differences among sites (inter-site) and among trees within sites (intra-site) for density, microfibril angle (MFA) and modulus of elasticity (MOE_d) as a function of cambial age. A linear model was fitted for density, an asymptotic exponential model for microfibril angle, and a three-parameter logistic sigmoidal model for modulus of elasticity.

Wood property and parameters	INTER-SITE (Among sites)				INTRA-SITE (among-trees)		
	Strathblane mean (s.e.)	Geeveston mean (s.e.)	Florentine mean (s.e.)	F _{2,37}	Strathblane F _{20,344-365}	Geeveston F _{9,174-184}	Florentine F _{8,138-147}
Density							
Intercept	566.4 (8.9)	516.7 (16.8)	502.2 (15.8)	10.0 ***	2.8***	3.3***	2.1*
Slope	5.5 (0.9)	10.9 (1.6)	8.4 (1.6)	6.0 **	1.4 ^{ns}	4.4***	4.8***
MFA							
Asym	7.8 (0.3)	7.5 (0.7)	6.7 (0.7)	1.4 ^{ns}	2.7***	5.2***	4.1***
R0	22.6 (0.6)	23.2 (1.1)	22.9 (1.0)	0.1 ^{ns}	3.6***	1.3 ^{ns}	5.5***
Lrc	-0.97 (0.1)	-1.5 (0.1)	-1.6 (0.1)	15.6***	1.2 ^{ns}	5.0***	4.9***
MOE _d							
Asym	18.9 (0.6)	21.1 (1.4)	21.4 (1.6)	2.1 ^{ns}	3.5***	5.9***	5.6***
Xmid	0.8 (0.3)	3.2 (0.7)	3.5 (0.8)	9.8***	1.3 ^{ns}	5.3***	4.2***
Scal	3.1 (0.3)	4.6 (0.5)	5.7 (0.6)	12.4***	1.1 ^{ns}	2.0*	1.5 ^{ns}

^{ns} Not significant P>0.05, * P< 0.05, **P < 0.01, ***P<0.001

MFA

Trees from the same site also tended to differ significantly in their pattern of radial change in MFA angle with age (Figure 4.2 and Table 4.3). All model parameters (Asym, RO and Lrc) were significantly different among trees in the Florentine site. At the other two sites, at least one parameter did not show significant differences among trees. While sites differed in their rate of curvature change in MFA (Lrc), they did not differ in their value at the pith (i.e. RO ranged from 22.6° to 23.2°) or asymptote (i.e. Asym ranged from 6.7° to 7.8°) which appear to be very stable. Thus while no site differences were detected in area-weighted means (Table 3.2), differences between inner- and outer-most wood (Table 4.2 and Table 4.3), or the pith and asymptote values, modelling did detect differences in the way the transition occurred. The most rapid decline in MFA towards the asymptote (ie. greatest Lrc) was evident at Strathblane, followed by Geeveston and finally Florentine. For example, the wood from the low productivity site at Strathblane dropped to a 10° MFA after 5 years growth from the pith, while Geeveston and Florentine took 8.2 and 7.9 years respectively (Figure 4.2).

An important issue is how far the stable plateau of MFA values (i.e. the region where MFA values are relatively uniform across rings) extends through the radial profile, because it has a direct impact on wood shrinkage and the stability of veneers sheets. The extent of the plateau of MFA values based on plot inspections is here defined as the region in which differences in MFA values between rings are equal to or less than one percent. Under this criterion, Strathblane reached stability at year 11, while Geeveston and Florentine reached stability in year 16 and 17, respectively.

MOE_d

The three parameter logistic function fitted for MOE_d revealed most variation between trees within sites occurred in the Asym parameter and least in the Scal parameter of the curves (Table 4.3). This difference in intra-site variation was reflected in site differentiation with the most differences among sites occurring in the Scal parameter and no significant differences being observed for the Asym

parameter. Xmid and Scal parameters both had significant differences among sites. The function fitted for MOE_d revealed that the asymptote values ranged from 18.9 to 21.4 among sites. Strathblane clearly exhibited the most abrupt increase in MOE_d, however, there were no major visual differences among the other two sites (Figure 4.2 and Table 4.3).

The proportion of MOE_d over 14 GPa was substantially higher at Strathblane than the other two sites, with a significant difference among sites in the age at which this threshold was achieved ($F_{2,37}=23.2$, $P<0.001$). The low productivity Strathblane site reached this threshold more than 2 and 3 years earlier, than the Geeveston and Florentine sites respectively. Similarly, the predicted MOE_d at the pith was significantly different among sites ($X=0$, $F_{2,37}=4.7$, $P=0.02$), with the highest values (8.6 GPa) occurring at the Strathblane site (Figure 4.2).

At the tree level across all sites the age at which the threshold MOE_d of 14 GPa was surpassed was highly negatively correlated with the area-weighted mean MOE_d ($n=40$; Pearson's $r=0.66$ with $p<0.001$). This means that the earlier the threshold was crossed the greater the average MOE_d of the tree, so the site rankings were the same for area-weighted mean and years with MOE_d above the threshold (Table 4.1 vs. Figure 4.2).

4.3.2.2.2 Radial change with percent of area

The results from analysing the radial change as a percent of area were similar to those produced by the cambial age analysis (Figure 4.3 and Table 4.4). The main dissimilarities involved MOE_d, where there was a differences in the magnitude and significance of the Scal parameter among trees within sites as well as among sites and a differences in the Xmid parameter differences among sites. These differences indicate that when scaled by percent area the differences in rate of curvature in approaching a similar asymptote are accentuated. As with the cambial age analysis the main difference in these curvature parameters (Xmid and Scal), involved differences of the low productivity Strathblane site from the two other sites.

The differences among sites in the proportion of wood over 14 GPa was similar to that found in the cambial age analysis ($F_{2,37}=21.9, P<0.001$), but the mean differences were more accentuated. At harvest, 85% of the wood from the Strathblane plantation was above the 14 GPa threshold compared with 70% and 64% for Geeveston and Florentine respectively. In contrast to the results of cambial age analyses, there were no differences among sites in the predicted MOE_d values in the pith (intercept $X=0$; $F_{2,37}=0.74, P=0.484$). The absence of site differences in pith and asymptotic values of MOE_d (Table 4.4) was not consistent with the significant results obtained for the difference between the inner- and outer-most wood (Table 4.2).

Consistent with cambial age results, but with reverse sign, the percent of area exceeding the MOE_d was positively correlated with the area-weighted mean MOE_d ($n=40$; $r=0.59, P<0.001$). Additionally, the site rankings for MOE_d were the same with Strathblane always highest and Florentine always lowest (Table 4.1 vs. Figure 4.3).

In relation to intra-site differences, the main difference to the cambial age analysis was an increase in the significance of the difference among trees in their curvature parameters for both MFA (Lrc) and MOE_d (Scal) (Table 4.3 vs. Table 4.4). For MOE_d , Scal values at the Florentine and Strathblane site were significantly different among trees using percent of area but not when using cambial age. In addition, trees at the Strathblane site showed no significant difference in Lrc for MFA with cambial age (Table 4.3), but a significant difference was evident with percent of area (Table 4.4).

Table 4.4 Model parameter means and standard errors (in parenthesis), F ratios and the significance of differences among sites (inter-site) and among trees within sites (intra-site) for density, microfibril angle (MFA) and modulus of elasticity (MOE_d) as a function of percent of area. A linear model was fitted for density, an asymptotic exponential model for microfibril angle, and a three-parameter logistic sigmoidal model for modulus of elasticity.

Wood property and parameters	INTER-SITE				INTRA-SITE		
	Strathblane mean (s.e.)	Geeveston mean (s.e.)	Florentine mean (s.e.)	F _{2,37}	Strathblane F _{20,344-365}	Geeveston F _{9,174-184}	Florentine F _{8,138-147}
Density							
Intercept	572.2 (8.5)	526.4 (16.0)	511.3 (14.9)	9.8***	3.5***	3.4***	2.3*
Slope	1.0 (0.2)	2.0 (0.3)	1.4 (0.3)	7.1**	1.3 ^{ns}	4.3***	5.2***
MFA							
Asym	8.0 (0.3)	8.0 (0.7)	7.7 (0.5)	0.1 ^{ns}	4.1***	6.0***	9.3***
R0	23.6 (0.7)	23.0 (1.2)	22.3 (1.0)	0.7 ^{ns}	5.4***	1.2 ^{ns}	6.3***
Lrc	-2.2 (0.1)	-2.8 (0.2)	-2.9 (0.2)	10.8***	2.6***	7.6***	9.1***
MOE _d							
Asym	18.6 (0.6)	20.1 (1.2)	19.5 (1.3)	0.9 ^{ns}	4.7***	7.6***	11.5***
Xmid	2.7 (1.6)	12.0 (3.4)	10.5 (3.6)	5.0*	1.3 ^{ns}	5.9***	9.9***
Scal	10.7 (1.4)	21.2 (2.9)	26.9 (3.1)	17.0***	1.8*	2.4*	3.7***

^{ns} Not significant P>0.05, * P< 0.05, **P < 0.01, ***P<0.001

4.4 Discussion

4.4.1 Significant radial change in wood properties

The current study revealed marked differences within trees between inner- and outer-wood in density, MFA and MOE_d in *E. nitens*. These differences are consistent with differences in wood properties between what is termed juvenile and mature wood observed in other eucalypt species (Downes *et al.* 2014; Lima *et al.* 2004).

A site effect on the differences between outer wood and inner wood extremes was detected as statistically significant only for density and MOE_d (using ten-percent extremes). In *E. globulus*, Downes *et al.* (2014), not only detected differences among sites in the difference between inner- and outer-wood for density and MOE_d, but also MFA using comparable methodology. Possible explanations for these additional site differences could be inherent species differences or the more limited environmental variation among the *E. nitens* sites in the present study in factors such as *rainfall*. According to Downes and Drew (2008) wood properties like density and MFA are significantly affected by water availability. For example, density increases in response to a reduction in water availability (Downes *et al.* 2006) and MFA decreases with increasing water stress (Drew *et al.* 2009).

Although the methodology of using differences between inner- and outer-wood can be effective when comparing the radial change between sites this approach provides no insight into the rate of transition between inner and outer wood characteristics. There are *remarkably* few studies modelling the radial change in hardwoods such as *E. nitens* (Sattler *et al.* 2014).

4.4.2 Patterns of radial change in wood properties

The patterns of change from pith to cambium in density, MFA and MOE_d found in this study were clear and matched trends in other studies of *Eucalyptus* (Downes *et al.* 2014; Lima *et al.* 2004; Medhurst *et al.* 2012).

Density was described appropriately by simple linear regression models. Downes *et al.* (2014) also used simple linear regression models in *E. globulus*, whereas

McGavin *et al.* (2015) used a sigmoidal four parameter logistic function to describe density in *E. nitens*. In the current study this sigmoidal function fitted when evaluated with respect to percent of area, but failed to converge for cambial age (Appendix A). Thus, this function was not used due to its inability to simultaneously capture the trends of density with respect to cambial age and percent of area.

An asymptotic exponential model appropriately represented the radial trend in MFA, revealing a rapid drop during the first years followed by a less rapid decrease, consistent with previous studies in hardwoods (Donaldson 2008). The conifers that have been studied exhibit the same trend. The main models used for MFA are logistic models fitted as a function of ring number from the pith (Jordan *et al.* 2005; Moore *et al.* 2014), but such models were not successful when applied in our study (Appendix A). This may be due to greater radial change in conifer MFA values. According to Donaldson (2008) conifers vary more than hardwoods, with drops in values from $\sim 45^\circ$ to $\sim 11^\circ$ to in comparison with, for example, *E. nitens* where MFA in the present study dropped from $\sim 22^\circ$ to $\sim 8^\circ$.

For MOE_d , the use of a three-parameter logistic model was in accordance with the general trends in radial change found in previous studies of *E. nitens* (Harwood *et al.* 2005b; Medhurst *et al.* 2012). McGavin *et al.* (2015) also used a logistic function to model the trends but with four parameters. The shape of the logistic model accords with the structural integrity theory in trees, as described by Lachenbruch *et al.* (2011). Lower MOE_d in early stage growth (core wood) increases stem flexibility and thus allows young trees to bend with external forces like wind and snow. As the trees increase in size, however, the stems require increasing stiffness in order to avoid failure due to environmental factors and their own weight. At a certain stiffness value the increment stops and stiffness remains relatively constant (asymptote), which is believed to help distribute the bending stress produced by environmental factors, especially wind, over a large area (Archer 1987; Lachenbruch *et al.* 2011).

4.4.3 Use of age or distance from pith

Both independent variables, cambial age and percent of area (size), produce equivalent results for site level data and very similar results for tree level data in the models applied.

Despite differences in growth strategies between sites in the current study, which are a consequence of differences in silviculture and environmental growth conditions, this was not reflected in a better performance of models fitting cambial age (Burkhart and Tomé 2012).

According to Kojima *et al.* (2009), *Eucalyptus* spp. xylem maturation directly affects wood properties, and is controlled by cambial age.

However, as there were no major differences between models based on cambial age and percent area, it may be possible to avoid the measurement of the ring boundaries when modelling radial variation in wood properties. This complex task, is time consuming and, more importantly, susceptible to error, especially in *E. nitens* which is prone to producing false rings (Hudson *et al.* 1998).

Nevertheless, it is not possible to dismiss the limitations of using percentage area when the purpose of the model is to determine the impact of factors such as rotation length and silviculture on whole-tree wood properties

Another advantage of using percent area rather than cambial age to predict the percentage of logs or trees with specific wood properties is its economic interpretation. In the current study, the percentage area of wood above the predefined threshold for MOE_d of 14 GPa is significantly affected by site. In particular, the higher proportion of stem area above this threshold at Strathblane appears to be a consequence of the low productivity of the site, rather than differences in silviculture. Strathblane is the lowest productivity site, but has larger average DBH (due to thinning and pruning) than trees in the highest productivity site at Florentine, which were not thinned. Downes *et al.* (2014) obtained similar results with *E. globulus*, in a study that evaluated the interaction between stocking

and fertilisation on the differences between inner and outer-wood, finding significant differences due to fertilisation but not stocking.

Using percent area as the independent variable gives the opportunity to evaluate the economic implications of silviculture and growing conditions more easily, quickly and accurately, and thus to define the best processing strategies according to the targeted final products, and ultimately to define the value of logs and forests (McGavin *et al.* 2015). The longest radial axis was sampled for practical reasons at the time of sample cutting. In hardwoods, excessive eccentricity of the pith might be associated with tension wood development, so using the longest axis in the disk could result in the inclusion of more tension wood in the samples. However, according to (Washusen 2011), while tension wood has serious impact on recovery or product quality in *E. globulus*, damaging levels of tension wood appear to be less common in *E. nitens*. Consequently, although it is not possible to dismiss the possibility that tension wood is included in the samples taken, the chance is low.

4.4.4 Tree and site differences in radial variation

In forest trees, the magnitude of the radial variation in wood properties such as density, MFA and MOE, depends on growing conditions, silviculture and environment conditions (Zobel and van Buijtenen 1989b). In the present study, significant differences were obtained in the pattern of radial variation in wood properties among trees within sites. Nevertheless significant differences were also detected between sites in these patterns. This is consistent with the statement of Zobel and van Buijtenen (1989b) that wood properties vary significantly among trees within sites and among sites.

Density

The linear model fitted for density showed that site differences were due to differences in both the intercept (pith density) and slope (rate of increase). The highest density in the pith of Strathblane trees could be a consequence of unfavourable site growth conditions in the early stage of the plantation. Such conditions would be expected to reduce vessel area and increase cell wall thickness,

resulting in higher density wood (Downes *et al.* 1997; Wimmer *et al.* 2002a). The opposite situation would therefore apply at Florentine, which had the lowest density and was a good quality site. Geeveston had the highest growth rate among our sites and also had the highest rate of radial increase in density. Although Downes *et al.* (2006) found no significant effect of growth rate on density in *E. nitens*, the results of the current study could be a consequence of an interaction between silviculture and site quality.

MFA

For MFA, the asymptotic exponential model showed pith values similar to those reported by Medhurst *et al.* (2012), but slightly higher than those found by Evans *et al.* (2000), in *E. nitens*. Asymptote values in these previous studies, however, were notably higher than reported here. This difference could be a consequence of the height of sampling, as in Evans *et al.* (2000) and Medhurst *et al.* (2012) the samples were taken at DBH (1.3 m), whereas the samples in the present study were taken at 2.5 m.

The lack of a significant site effect for either the asymptote or pith values in our study only partially agrees with results from Lima *et al.* (2004), who found site effects in pith values but not in outer wood. This difference could be due to differences in species and growing conditions, as Lima *et al.* (2004) worked with clones of *E. grandis* x *E. urophylla* growing in Brazil in a warm climate. Lima *et al.* (2004) also reported a genetic influence on MFA, but it is not clear whether genetics or site had the greater influence.

In *E. nitens*, Wimmer *et al.* (2002b) found a positive relationship between growth rate and MFA, so factors that influence growth rate could also affect the rate of decline in MFA from pith to cambium. In the current study, the Strathblane plantation was established on a poor quality site, with the result that DBH measurements were significantly lower than at Geeveston despite a very similar silvicultural treatment. However, MFA values at Strathblane reached 10° by 5 years while Geeveston trees took 7.6 years to show the same decrease. On the other hand, Geeveston and Florentine had very different silviculture treatments but

similar site quality. Geeveston exhibited the largest DBH, probably due to thinning, but a slightly (yet significantly) lower rate of decline in MFA than at Florentine. Of the sites studied, Geeveston had the greatest exposure to wind (refer to Table 2.1) that, in conjunction with thinning, would produce higher risk of stems breaking. According to Lachenbruch *et al.* (2011), trees need to increase wood stiffness with age/size to avoid stem fracture due to self weight and wind, and because of high stiffness is highly correlated with low values of MFA, a decrease in MFA value would increase stiffness (Donaldson 2008). Thus under this hypothesis, Geeveston trees would be expected to produce lower MFA values earlier than Florentine to increase their stiffness in response to higher wind exposure.

MOE_d

The sigmoid model evaluating the modulus of elasticity showed that asymptotic values of MOE_d did not differ statistically among sites, with an average across sites of 19.4 GPa. This average asymptote is 19% larger than reported by McGavin *et al.* (2015) using sample strips of veneers obtained from logs from the same trees as the current study, presumably due to differences in sampled methodology applied. McGavin *et al.* (2015) measured MOE_d using strip samples from the veneer, cut parallel to the grain between 0.5 m above the ground to 2.5 m above the ground, which may have included natural defects, whereas the SilviScan estimates of MOE_d were measured using clear wood samples obtained a height of 2.5 m (Yang and Evans 2003).

The lack of difference among sites in the MOE_d asymptote could be associated with stabilisation of a mature wood zone. According to Zobel and Sprague (1998) mature wood is where wood has more constant characteristics (e.g. MOE_d) and this is determined by an interaction of silviculture, environmental and genetic factors. In this study the sites had differences in silviculture and environment growing conditions. There is no precise information about genetic stock, however, most Tasmanian *E. nitens* plantations established approximately 20 years ago were from open-pollinated seed from Central Victoria (Hamilton and Potts 2008). Thus, the

similar MOE_d asymptote could reflect the similar genetic stock reaching the same value regardless of growing conditions and silviculture.

In contrast to the lack of differences in asymptote values, there were significant differences in the scale and inflection point parameters among sites for MOE_d. These parameters reflect the rate of radial change in the trees. Day and Greenwood (2011) consider that radial development is controlled by both intrinsic (gene expression) and extrinsic (environmental factors). However, the same authors recognised that it is very difficult to determine which is most influential. However, in a study of outer wood MOE and density in *Pinus radiata*, a bigger influence of site and silviculture than genetics has been shown (Carson *et al.* 2014). Although, *Pinus radiata* is not directly comparable with *Eucalyptus* spp. and such comparisons will depend upon the range of genetic and site treatments compared, may provide an indication the influence of extrinsic factors in forest plantations. Environment, silviculture and possibly genetic factors varied among sites in our study. Consequently, it was not possible to identify the specific factors that were responsible for the observed differences in radial trends among sites.

In conclusion, although the radial variation models have shown an accurate and reliable representation of trends of wood properties through tree radii, it is time consuming to develop these models due to the complexity of intra- and inter-site variation. An alternative method, especially for sites with large variation in environmental conditions, would be to use the area weighted means of the wood properties. In this study, there was a significant effect of site on the proportion of the stem area with a MOE_d above a predefined threshold, but not using the area-weight tree mean. Nevertheless, the site rankings were the same and there was a highly significant correlation between these measures at the tree level. This result indicates that it would be possible to use the area weighted tree means to analyse the differences between sites, which would account for the non-linear trends in wood properties.

Chapter 5 The characterisation of the wood properties of Tasmanian *Eucalyptus nitens* plantations

5.1 Introduction

The forest and wood processing industry produces a variety of products based on the market demand and specific wood properties of available forest resources. The inherent wood properties are crucial, as they influence how the wood will respond to processing and the quality of the final product (Leban and Jaeger 1999; Lundqvist *et al.* 2009; van Leeuwen *et al.* 2011). Important properties used to assign wood products to different processes include density and modulus of elasticity (MOE). Accurate prediction of the quantity of wood with desired properties within existing forest resources, therefore, would enhance the ability of processors to optimize resource use and plan for current and future market demands (Wood *et al.* 2008).

Product-critical wood properties vary both within and between trees and sites, and are affected by a broad range of factors including genetics, climate and other environmental factors, forest characteristics including age. Genetic pedigree of the plantations was not available (although are likely to be at least the same race) and in terms of forest characterisation this thesis focused on the other factors, as discussed below in Section 5.1.1. The nature and relative importance of these influences is likely to vary between species and geographic regions. In the context of this thesis, therefore, forest characterization is defined as the quantitative prediction of wood properties across a given region, based on forest variables (i.e. characteristics measured from the trees or stand), environmental variables (which here includes non-climate variables as well as latitude, longitude and elevation) and climatic variables (which here includes Bioclim-derived variables related to temperature and precipitation. As direct measurement of these wood attributes is costly and time consuming, the development of alternative methods such as accurate predictive models is a priority for quantifying available forest resources (Lessard *et al.* 2014). While process-based models are being developed for wood

properties of forest trees (Downes *et al.* 2009a), there are few spatially-explicit empirical models published to date for wood properties, and these are mainly for softwoods (Antony *et al.* 2011; Jordan *et al.* 2008; Palmer *et al.* 2013). A more recent example is a study using climatic and environmental factors to predict wood fibre attributes in Canadian conifers (Lessard *et al.* 2014). Searches of the literature revealed no such published empirical models for eucalypt species.

5.1.1 Factors that affect wood properties

Tree or stand age is recognized as one of, if not the most important factor influencing wood properties, due to its direct effect on the percentage of juvenile wood (Zobel and Buijtenen 1989a). The wood closest to the pith is known as juvenile wood on account of the young age of the tree when this layer was formed and generally has lower density and MOE and higher MFA than ‘mature’ wood close to the cambium (Lachenbruch *et al.* 2011). According to Kojima *et al.* (2009) in *Eucalyptus* wood maturation is controlled by cambium age, so formation of mature wood starts once a certain cambium age is attained. As demonstrated previously in Chapter 4 for *E. nitens*, wood properties vary across the stem radius, with density increasing linearly, MFA decreasing asymptotically, and MOE increasing sigmoidally from the centre of the tree (the pith) to the outer layers (the cambium). Juvenile wood also shows the highest rate of change of wood properties, with wood property values stabilising in the mature wood (Lachenbruch *et al.* 2011). Older trees, which have a higher proportion of mature wood, therefore have higher overall values for density and MOE and lower overall values for MFA, and a larger proportion of wood with similar characteristics.

The influence of water availability on wood properties has been observed at different scales, including at the level of the cells, tree rings, trees and sites (Zobel and Buijtenen 1989b). At the cellular level, short-term variation in environmental conditions can create detectable differences in wood properties throughout the stem radius by influencing cell development (Lachenbruch *et al.* 2011). For example, Drew *et al.* (2009) were able to detect the influence of daily variation in environmental conditions on density and MFA of *E. globulus*. These influences were

mainly attributable to differences in water availability, with lack of available water associated with increases in density and decreases in MFA values. In *E. nitens*, Wimmer *et al.* (2002b) also found that MFA increased in response to water stress release. Seasonal changes in rainfall and temperature also produce wood with different characteristics. For example in four year old *E. nitens*, the latewood (produced in summer) was shown to be 104 kg m^{-3} more dense than early wood (produced in spring) (Knapic *et al.* 2013). Longer term differences in water availability can also be seen at the tree level. Beadle *et al.* (2001) found that irrigated trees of *E. nitens* had lower density and longer average fibre length when compared with trees without irrigation.

Water availability shows a strong influence on wood properties at the site and regional level. At these levels, water availability for trees is dependent on a number of other environmental processes including geology, soil type, intensity and frequency of water inputs, runoff and evaporation. In previous studies, however, models have generally indicated that precipitation variables have been the most predictive of changes to wood properties. Of three *E. globulus* study sites, Downes *et al.* (2014) found the highest mean wood density (648 kg m^{-3}) at the site with lowest annual rainfall, lowest climate wetness index and soil water-storage capacity, and lowest density at the site with highest rainfall. No examples were found in the literature for the regional scale influence of water availability on hardwoods, however, significant regional variation was observed for MOE and MFA in Loblolly pine, which was ultimately thought to be driven by factors such as rainfall and temperature (Antony *et al.* 2011). More specifically, Lessard *et al.* (2014) showed that rainfall (which had a negative influence) was the second most influential variable for predicting density in conifers, after the age of the site.

As can be seen from the above examples, the relationship between water availability and wood properties appear to remain consistent across multiple scales, although the magnitude of changes may vary. In general in *Eucalyptus*, density and MOE values tend to increase in response to water stress, whereas MFA values decrease.

5.1.2 Modelling methodology for forest characterisation

Studies on wood properties on Eucalyptus plantations have mainly focused on the relationship between wood properties and site variables, like silviculture, irrigation and fertilization. Wood density is the most common wood property evaluated in forest characterisation, due to high relation between wood density and other wood properties. Furthermore, this wood property is simple and easy to collect (Downes *et al.* 1997). A variety of statistical techniques have been used during model development, such as analysis of variance, generalized linear models, linear mixed effects models, ordinary least squares regression, path analysis, and stepwise regression (Auty and Achim 2008; Auty *et al.* 2014; Auty *et al.* 2013; Downes *et al.* 2014; Moore *et al.* 2014; Sattler *et al.* 2014; Wimmer *et al.* 2002b). In addition, improvements in geospatial analysis techniques have meant that it is now possible to develop spatial models for wood properties that are based on underlying variations in soil and climatic factors, which in turn can be obtained from spatial information (van Leeuwen *et al.* 2011). An example of such a model is that developed by Palmer *et al.* (2013) for predicting wood density of *Pinus radiata* across New Zealand.

These studies support the idea that environmental and climatic variables influence wood properties and provide promising avenues to develop predictive models at the regional scale. Only a few studies were found which modelled product-critical wood properties of a forest tree resource using a broad range of environmental and climate variables. The most comprehensive was that of Lessard *et al.* (2014), who developed models for a conifer species. This study used multiple regression, and differentiated between candidate models using Akaike's information criterion (AIC) (Akaike 1974) which estimates the quality of each model, relative to each of other models. Because there is always going to be a trade-off between the goodness of fit and the number of parameters required by parsimony. AIC is useful because it explicitly penalizes any superfluous parameters in the candidate model (Crawley 2007).

5.1.3 Aims

The aims of the present study were to characterise the variation in the Tasmanian *E. nitens* plantation resource for wood properties relevant to the production of structural veneer. The specific objectives were to:

- identify forest, environmental and climatic variables that can predict product-critical wood properties;
- develop predictive models for wood properties; and
- predict the spatial variation in wood properties across the Tasmanian plantation estate.

5.2 Materials and methods

5.2.1 Site selection and sample preparation

The sites used to develop the models were from *E. nitens* plantations in Tasmania, Australia owned by Forestry Tasmania (46 sites were used to develop models and 13 sites for validation). The felled trees from which disks were obtained were part of a larger long-term project of Forestry Tasmania aimed at developing robust taper functions for trees of diverse age from across their estate. The disks obtained for the present study were from trees felled in 2013 and 2014 and can be considered a random sample of the estate. Of the plantations sampled for this study, 41% had been thinned with different intensities and while the age of thinning was unknown, the plantations themselves ranged in age from 2 to 22 years. The unthinned plantations ranged in age from 3 to 23 years. The sites selected adequately represented the different growing conditions and environmental conditions present across the *E. nitens* plantations in most of Tasmania, with the exception of the northwest of the island (Figure 5.1).

For each site selected based on GIS forest inventory information, a circular plot with 12 m radius (452 m²) was located with a GPS. Three representative trees were selected from each plot, one for each three size classes (small, medium and large), based on the distribution of tree heights and diameters at breast height over bark (DBH, measured at 1.3m). Immediately after felling, one 50 mm thick disk was obtained from each tree at breast height (1.3m). The disk was placed in a plastic bag to avoid dehydration. Afterwards the disks were stored in a freezer (-18 °C) for a period of 3-6 months, and then moved to another freezer (-15°C) during processing.

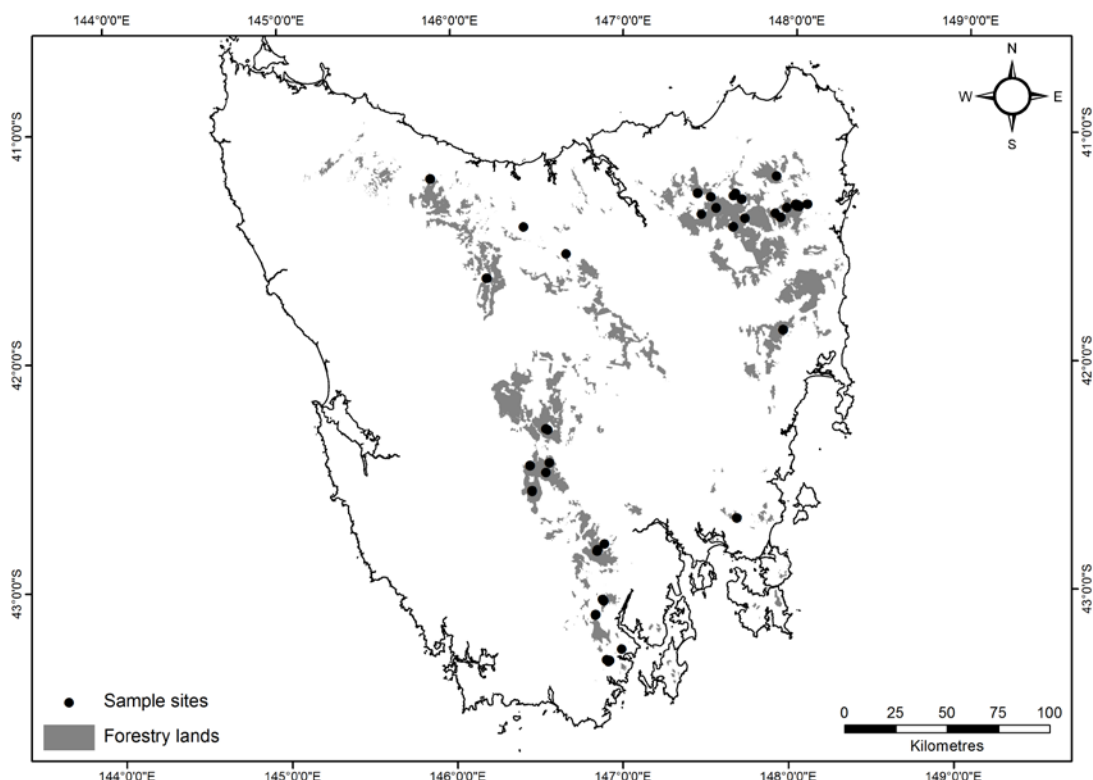


Figure 5.1 Location of sampled sites across Tasmania. The surface has been clipped according to areas of land managed by Forestry Tasmania available for production forestry under the Tasmanian Forest Management Act 2013.

The details of sample preparation and their measurement using SilviScan are described in Section 4.2.2. In brief, a radial block sample (clear of defects), 20 mm (longitudinally) x 15-20 mm (tangentially) x longest radial axis of disk (radially) was cut from each of the disks. These samples were dehydrated by successive ethanol baths (70%, 90 % and 100%), following the methodology described by Evans *et al.* (2000) to prevent collapse, cracking and distortion during air-dry drying (8% moisture content) and storage. From each dried block sample, one strip sample (2 mm tangential plane x 8 mm longitudinal plane) was obtained using a twin-bladed saw for SilviScan-3™ analysis (Downes *et al.* 2014). SilviScan was used to simultaneously assess density, MFA and MOE_d from pith to cambium on the radial face of the strip samples. Density was obtained with 0.025 mm resolution, MFA with 1-mm resolution, and MOE_d was calculated using density and MFA data at the resolution of MFA data (Evans and Ilic 2001).

5.2.2 Data analysis

Firstly, differences in wood properties among the three size classes were analysed with separate one-way ANOVAs, using the *anova* function of R (R Core Team 2015). This model included tree size class and site as main fixed effects and plantation age as a covariate. To evaluate the influence of growing conditions and the environment/climate variables on density, MFA and MOE, models for each wood property were fitted using site level data. The models were developed with wood properties as response variables (Y) and explanatory variables (X) included various forest, environmental and climatic variables. The models were developed firstly with a training data set that included 46 sites, and then validated using data from 13 independent sites. The wood properties were estimated using SilviScan-3™ radial scans. For each tree the area-weighted mean density, MFA and MOE_d were estimated from the SilviScan-3™ radial scans (Downes *et al.* 1997). This methodology assumed disks were circular and that there was no pith eccentricity. The raw data for the modelling comprised site means, and the data summary is showed for the training and validation sets in Table 5.1.

Table 5.1 The number of the sites, the mean, standard deviation (SD), minimum (Min) and maximum (Max) of the area weighted tree means of density, MFA and MOE measured by SilviScan. The raw data were the averages for sites in the training and validation sets.

Wood property	Training set					Validation set				
	n	Mean	SD	Min	Max	n	Mean	SD	Min	Max
Density (kg m ⁻³)	46	583.4	72.3	461.9	829.0	13	598.6	96.1	490.9	774.5
MFA (degrees)	46	14.5	3.2	4.8	27.6	13	15.3	3.9	6.2	21.5
MOE (GPa)	46	12.4	2.9	7.4	23.8	13	12.2	3.9	8.2	23.5

There were three main groups of explanatory variables: forest, environmental and climatic (Table 5.2). The first two groups were provided by Forestry Tasmania from their standard field assessments of plantations (refer to Table 5.2 for more detail). The last one was climatic surface data from Tasmania, processed using the BIOCLIM program which is part of the ANUCLIM Version 6.1 software package (Fenner School of Environment & Society 2015). A total of 46 sites were used as a training set to develop the models. These stands had an average age of 13.5 years (range 3 to 24

years), average elevation of 505 m asl (range 102 to 875 m asl) and average annual precipitation of 1210 mm (range 715 to 1685 mm). The validation set consisted of 13 stands with an average age of 12 years (range 3 to 24 years), average site elevation of 456 m asl (range 74 to 713 m asl) and average annual precipitation of 1160 mm (range 724 to 1580 mm).

Using site level data, linear models for each wood property were developed through the automatic stepwise backward regression approach to determine which forest, environment and climate variables significantly influenced density, MFA and MOE_d. In order to avoid overparameterisation the models were developed by grouping explanatory variables within the three main groups defined above, reducing the number of variables. This followed the recommendation of Crawley (2007) where the number of explanatory variables in the model should not exceed approximately one-third the number of samples at any one time. In addition, explanatory variables with a high correlation (Pearson $r > 0.90$) were not included in model development, to reduce the potential collinearity. Site age was included as a “permanent” explanatory variable in all the models. This variable was included to account for the age heterogeneity of the sites, as age is known to influence these wood properties (van Leeuwen et al. 2011), especially in Eucalyptus (Kojima et al. 2009, see also Chapter 4).

The models were fitted using the R procedure *lm* and the *step* function to identify and determine significant variables (R Core Team 2015). The *step* function eliminates variables in a step-down manner based on their impact on AIC values. As this is a conservative approach, and subsequent manual elimination of variables was undertaken in a stepwise manner as outlined in the R Book (page 447, Crawley 2007). In this case, elimination was based on the significance of the t-test derived from the regression coefficient estimate and its standard error.

The optimal models obtained for each group of explanatory variables and wood property were termed ‘full models’. After this, new models, called ‘simplest models’, were fitted with more easily understandable and measurable variables to facilitate use of these models by foresters and processors. The procedure described

above was also applied to obtain the final full and final simplest model that included all significant variables identified in the separate analyse of the forest, environmental and climate variables.

The final full and simplest models were validated with a sample of 13 independent sites, and their precision and accuracy of validations judged by the coefficient of determination (R^2), root mean square error of prediction (RMSEP), standard error of prediction (SEP) and Bias (Naes *et al.* 2002). Bias is defined here as the average difference between the original SilviScan value and the predicted value (Naes *et al.* 2002). Finally, spatial mapping of the variation of density, MFA and MOE_d through Tasmania were conducted using predicted values derived from the final simplest model. The maps were modelled assuming a plantation age of 10 (all properties) and 20 (MOE_d only) years.

Maps were created in ArcMap 10.2 (copyright ESRI Inc®). Input datasets used were the Annual precipitation raster, provided by the Environmental Change Biology research group at the University of Tasmania, and Digital Elevation Model (DEM), downloaded from the LIST Open Data website (Tasmanian Government 2015). Three constraints were used to delineate the area covered by the model. Firstly, all reserve areas were excluded (listed under the National Parks and Reserved Land Management Act 2002) using the 'Land tenure' polygon dataset supplied by the LIST Open Data website (Tasmanian Government 2015). Secondly, the DEM raster was limited to values between 74 and 875 m asl. Lastly, the annual precipitation raster was limited to values between 715 and 1685. The *Raster calculator* and *Minus* tools of ArcMap were used to apply the predictive models to each map pixel. The purpose of the constraints in elevation and precipitation was to limit the spatial representation to the same range of values used in model development.

Table 5.2 Explanatory variables divided into forest, environmental and climatic explanatory variables to develop models of density, MFA and MOE_d of *E. nitens*.

Variable	Description	Unit
Forest variables		
Stocking	Number of trees per hectare.	(tree ha ⁻¹)
Plantation Age	Plantation age (years).	(years)
Tree Diameter	Mean of sample tree diameter at breast height (under bark).	(mm)
Mean Height of Dominant Trees	Mean of dominant tree heights calculated from the 100 tallest trees per hectare in the plantation.	(m)
Mean Tree Basal Area	Mean tree basal area per hectare.	(m ²)
Site Volume	Stand volume per hectare.	(m ³)
Site Index	Defined as height of dominant and co-dominant trees in a stand at a base 15 years.	-
Environmental variables		
Latitude	The angular distance north or south from the equator of a point on the earth's surface, measured on the meridian of the point.	(°)
Longitude	The angular distance east or west on the earth's surface, measured by the angle contained between the meridian of the point and some prime meridian.	(°)
Elevation	Site height above mean sea level .	(m asl)
Direct Insolation	Yearly solar radiation measured perpendicular to Sun's rays, excluding diffuse insolation. Calculated using the Potential Incoming Solar Radiation from the SAG-GIS module v2.1.3.	(kWH m ⁻²)
Wind fetch	Fetch is a measurement of distance that indicates how far wind has travelled over open water. Calculated using the Potential Wind Effect from the SAG-GIS module v2.1.3.	-
Topographic position index	Topographic position index measured topographic elevation and slope positions in digital elevation models (Weiss 2004).	-
Soil wetness	Fraction of the total volume of soil that is occupied by the water contained in the soil. Calculated using the Topographic Wetness Index from the SAG-GIS module v2.1.3.	-
Climatic variables		
Annual Mean Temperature	The mean of all the weekly mean temperatures. Each weekly mean temperature is the mean of that week's maximum and minimum temperature.	(°C)
Isothermality	The mean diurnal range variable divided by the Annual Temperature Range variable.	
Temperature Seasonality	The temperature Coefficient of Variation is the standard deviation of the weekly mean temperatures expressed as a percentage of the mean of those temperatures (i.e. the annual mean).	(%)

Table 5.2 (continued)

Variable	Description	Unit
Maximum Temperature of Warmest Week	The highest temperature of any weekly maximum temperature.	(°C)
Minimum Temperature of Coldest Week	The lowest temperature of any weekly minimum temperature.	(°C)
Temperature Annual Range	The difference between the Max Temperature of Warmest Period and the Min Temperature of Coldest Period.	(°C)
Mean Temperature of Wettest Quarter	The wettest quarter of the year is determined (to the nearest week), and the mean temperature of this period is calculated.	(°C)
Mean Temperature of Driest Quarter	The driest quarter of the year is determined (to the nearest week), and the mean temperature of this period is calculated.	(°C)
Annual Precipitation	The sum of all the monthly precipitation estimates.	(mm)
Precipitation of Driest Week	The precipitation of the driest week.	(mm)
Precipitation Seasonality	The Coefficient of Variation is the standard deviation of the weekly precipitation estimates expressed as a percentage of the mean of those estimates (i.e. the annual mean).	%
Precipitation of Driest Quarter	The driest quarter of the year is determined (to the nearest week), and the total precipitation over this period is calculated.	(mm)

Note: Bioclim and other variables highly correlated (Pearson $r > 0.90$) with the variables listed were not included in the step-down analysis to avoid colinearity issues. Variables not included: Mean Tree Height, Stand Basal Area, Diffuse Insolation, Mean Diurnal Range, Mean Temperature of Warmest Quarter, Mean Temperature of Coldest Quarter, Precipitation of Wettest Week, Precipitation of Wettest Quarter, Precipitation of Warmest Quarter and Precipitation of Coldest Quarter. Forestry Tasmania provided Forest and environmental variables. (-) unitless index.

5.3 Results

5.3.1 Model fitting

Analysis of variance revealed no overall significant differences in wood properties among the three size classes. As such, tree size was not further considered as an explanatory variable in the model development and site averages modelled.

Significant differences were observed among sites for Density ($P < 0.001$), MFA ($P < 0.01$) and MOE ($P < 0.001$).

In combination with tree age, the forest, environmental and climatic variables were able to explain a significant component of the variation among sites in density, MFA and MOE_d, when models were developed with the training set (Table 5.3). The most relevant variable was plantation age, which alone explained 36.1, 43.3 and 52.6% of variance for density, MFA and MOE_d respectively, and as expected showed a highly significant effect on all three wood properties. In all cases density increased, MFA decreased and MOE_d increased with plantation age and the term was significant ($P < 0.05$) in all models except for the models using only forest variables.

Using the forest variables to evaluate the development of models the same explanatory variables were retained in both the full and simplest models (Table 5.3). Mean Height of Dominant Trees was the common significant variable among density, MFA and MOE_d. Tree Diameter was only significant in the MFA model, where its effect was positive. The models including these variables explained (R^2) 45.1%, 51.5% to 59.5% of the variation among sites for density, MFA and MOE_d, respectively, in the training set. Plantation Age was not significant in these models for density and MFA, and was only marginally significant for MOE_d ($P < 0.1$), and its effect was absorbed by the better explanatory variable Mean Height of Dominant Trees. The full model included the most practically assessed variables, so the simplest model for forest variables included the Mean Height of Dominant Trees for density, MFA and MOE_d and in addition, Tree Diameter for MFA (Table 5.3). In all cases, the inclusion of these significant forest variables explained between 6.9% and 9.6% more of the variation among sites than Plantation Age alone.

Table 5.3 Significant explanatory variables by group for the full and simplest linear models for density, MFA and MOE. The estimated parameters and their significance levels, model R^2 and the AIC are shown

Explanatory variable	Parameter estimate for models of					
	Density		MFA		MOE	
Age						
Intercept	499.8		18.3		8.3	
Plantation Age (years)	6.2 ***		-0.3 ***		0.3 ***	
Multiple R-squared	36.1		43.3		52.6	
AIC	494.5		196.0		185.6	
Forest variables						
Full model/Simplified model						
Intercept	472.9		19.0		7.3	
Plantation Age (years)	1.5		-0.1		0.1	
Mean Height of Dominant Trees (m)	3.7 *		- 0.2 **		0.1 **	
Tree Diameter (m ² /h)			0.01 *			
Multiple R-squared	45.1		52.9		59.5	
AIC	489.5		194.7		181.3	
Environmental variables						
Full model/Simplified model						
Intercept	575.3		16.6		10.6	
Plantation Age (years)	5.4 ***		-0.3 ***		0.3 ***	
Elevation (m asl)	-0.1 ***		0.003 *		-0.004 ***	
Multiple R-squared	55.3		49.5		63.4	
AIC	480.1		192.7		176.6	
Climatic variables						
Full model						
Intercept	171.7		7.7		15.2	
Plantation Age (years)	6.9 ***		-0.3 ***		0.3 ***	
Max Temp Warmest week (°C)	20.1 **					
Annual Precipitation (mm)	-0.1 *				-0.01 **	
Precipitation Seasonality (%)			0.1 **			
Precipitation Driest Quarter (mm)			0.04 ***			
Multiple R-squared	62.4		64.9		73.0	
AIC	474.1		183.3		162.7	
Simplified model						
Intercept	453.7		11.2		15.2	
Plantation Age (years)	6.1 ***		-0.3 ***		0.3 ***	
Annual Mean Temperature (°C)	15.6 *					
Annual Precipitation (mm)	-0.1 *		0.01 ***		-0.01 ***	

Explanatory variable	Parameter estimate for models of		
	Density	MFA	MOE
Multiple R-squared	59.2	64.9	73.0
AIC	477.9	175.9	162.7

Table 5.3 (continued)

Explanatory variable	Parameter estimate for models of		
	Density	MFA	MOE
Final models			
Full model			
Intercept	352.3	7.7	15.2
Plantation Age (years)	7.4 ***	-0.3 ***	0.3 ***
Annual Precipitation (mm)	-0.1 *		-0.01 ***
Direct Insolation (W/m ²)	-0.03 *		
Max Temp of Warmest Week (°C)	18.7 **		
Precipitation of Driest Quarter (mm)		0.04 ***	
Precipitation Seasonality (%)		0.1 **	
Multiple R-squared	68.1	64.9	73.0
AIC	468.7	177.9	162.7
Simplified mode			
Intercept	647.1	11.1	15.2
Plantation Age (years)	5.7 ***	-0.3 ***	0.3 ***
Annual Precipitation (mm)	-0.1 *	0.01 ***	-0.01 ***
Elevation (m asl)	-0.1 *		
Multiple R-squared	60.1	64.9	73.0
AIC	477.1	182.6	162.7

*P<0.05; **P<0.01; ***P<0.001. The smaller the AIC value for a given trait the better. Note that Age was retained in all models regardless of its significance.

Plantation Age was highly significant (P<0.001) in all models that included the environmental explanatory variables, positively affecting density and MOE and negatively affecting MFA (Table 5.3). Of the environmental variables, site Elevation was the only variable retained in all models for all three wood properties in both the full and simplest models. Elevation had a significant negative effect on density and MOE_d and a significant positive effect on MFA. In combination with age, it explained between 49.5 and 63.4% of variance among sites for the three wood

properties (Table 5.3). Although, there are evidence that soil/fertilization information affects the wood properties for *Eucalyptus* (Downes *et al.* 2014) as well for softwoods (Beets *et al.* 2007), such information was not available in the present case.

For the climatic variables, the full model had a range of variables that significantly affected the three wood properties. However, Annual Precipitation was the only variable simultaneously affecting density and MOE_d (Table 5.3). Density was only affected by a temperature related variable. In all cases Plantation Age had a highly significant effect. In the simplest model using the climatic variables, the inclusion of the Annual Mean Temperature and Annual Precipitation were significant for density, but not for MFA or MOE_d where Annual Precipitation was the only significant variable. In comparison with the full model, the simplest model gave slightly lower R² for the density, but the same R² for MFA and MOE_d. The reduction in R² was 3.2% for density, and the AIC was higher by 3.8. Although, MFA had the same R² its AIC decreased by 7.4 due to fewer variables being fitting in the model. In the simplest models, therefore, Annual Mean Temperature and Annual Precipitation gave satisfactory results in terms of prediction of wood properties. These two climatic variables were significantly negatively correlated (n=63; Pearsons $r = -0.55$ $P < 0.001$), and both were significantly correlated with site Elevation (Annual Mean Temperature n=63, $r = -0.91$, $P < 0.001$; Mean Precipitation n=63; $r = 0.55$, $P < 0.001$).

The final full models were obtained by applying the stepwise methodology to all significant variables from each group analysis (plus direct insolation for Density which was significant in the earlier models at $P < 0.1$) after checking for co-linearity (i.e. $r < |0.9|$), and resulted in the inclusion of five variables (Table 5.3). The variables selected were mostly climatic variables with the exception of Direct Insolation in the density model. Temperature and precipitation variables both influenced density, however MFA and MOE_d were affected exclusively by precipitation variables. Annual Precipitation was the only variable present in models for more than one wood property. The remaining variables were represented in either the density or MFA models. MOE_d had Annual Precipitation as the only

significant variable. In the final simplest model, the application of the same methodology as in the final full model (i.e. stepwise methodology with significant variables from each group) gave similar R^2 results for MFA and MOE_d models as the final full models and a slight increase in AIC only for MFA. Annual Precipitation was the only variable that significantly affected these two wood properties. On the other hand, in the density model Annual Precipitation and site Elevation were included as explanatory variables, and there was an 8% decrease in R^2 and an increase of 8.4 in the AIC value between the final simplest and final full model.

5.3.2 Model validation

Data from thirteen sites randomly distributed across the plantation estate were used to validate the models. Overall, when the models were applied to the validation data set the R^2 ranged from 43 to 59.7%, which was lower than the R^2 of the models when they were developed in the training data set. Nevertheless, in all cases the model explained a statistically significant ($P < 0.05$) proportion of the variation among sites in the validation data set. The decrease in R^2 when models were applied to validate data (sites) were different among wood properties and the model type (full or simplest), ranging from a R^2 reduction of 5.2 to 19.9% in absolute values. The R^2 values from the density models decreased more in the full than the simplest model (21.3 and 17%, respectively), but in the case of MFA there was only a 0.1% of difference between both models with a 5.3% average decline. The MOE_d models showed a substantial decrease in R^2 values, with a 19.9% drop in the validation compared with the training data set. In validation statistics, density again showed the biggest differences between the full and simplest models with respect to RMSEP, SEP and bias, whereas MFA models showed same result in RMSEP and SEP between full and simplest models, while bias was lower in the simplest than in the full model (Figure 5.2 and Table 5.4).

It is important to mention that sites in the validation data set were sampled from the same geographical distribution, and on average were slightly younger than the training data set. Although the validation sites had the same geographical distribution, they differed marginally in Elevation and Annual precipitation from the

training data set. For example, while 62% of validation sites were located between 401 and 700 m asl, the training data set had only 38% of sites in this elevation range. Annual Precipitation for both data sets had a similar range, however more of the sites in the validation data set were in the upper range. For example, the training data set had 20% of sites in the range of 1201 to 1300 mm, whereas the validation data set had 23% of sites between 1401 to 1500 mm.

Table 5.4 Predictive tree-level statistics for density, MFA and MOE_d in the validation data set (n=13) for the full and simplest models.

Wood property	Type of model	R ² (%)	RMSEP	SEP	BIAS
Density	Full model	46.7[68.1]	64.8	64.2	-8.9
	Simplest model	43.0[60.1]	65.3	65.1	-5.5
MFA	Full model	59.7[64.9]	2.4	2.4	-0.1
	Simplest model	59.6[64.9]	2.4	2.4	0.02
MOE _d	Full & simplest model	53.1[73.0]	2.6	2.6	-0.2

R²: Coefficient of determination; RMSEP: Root mean square error of prediction; SEP: standard error of prediction.

Note: The statistics for the training data set are in Table 5.1 but the R² values are shown in square brackets for comparison.

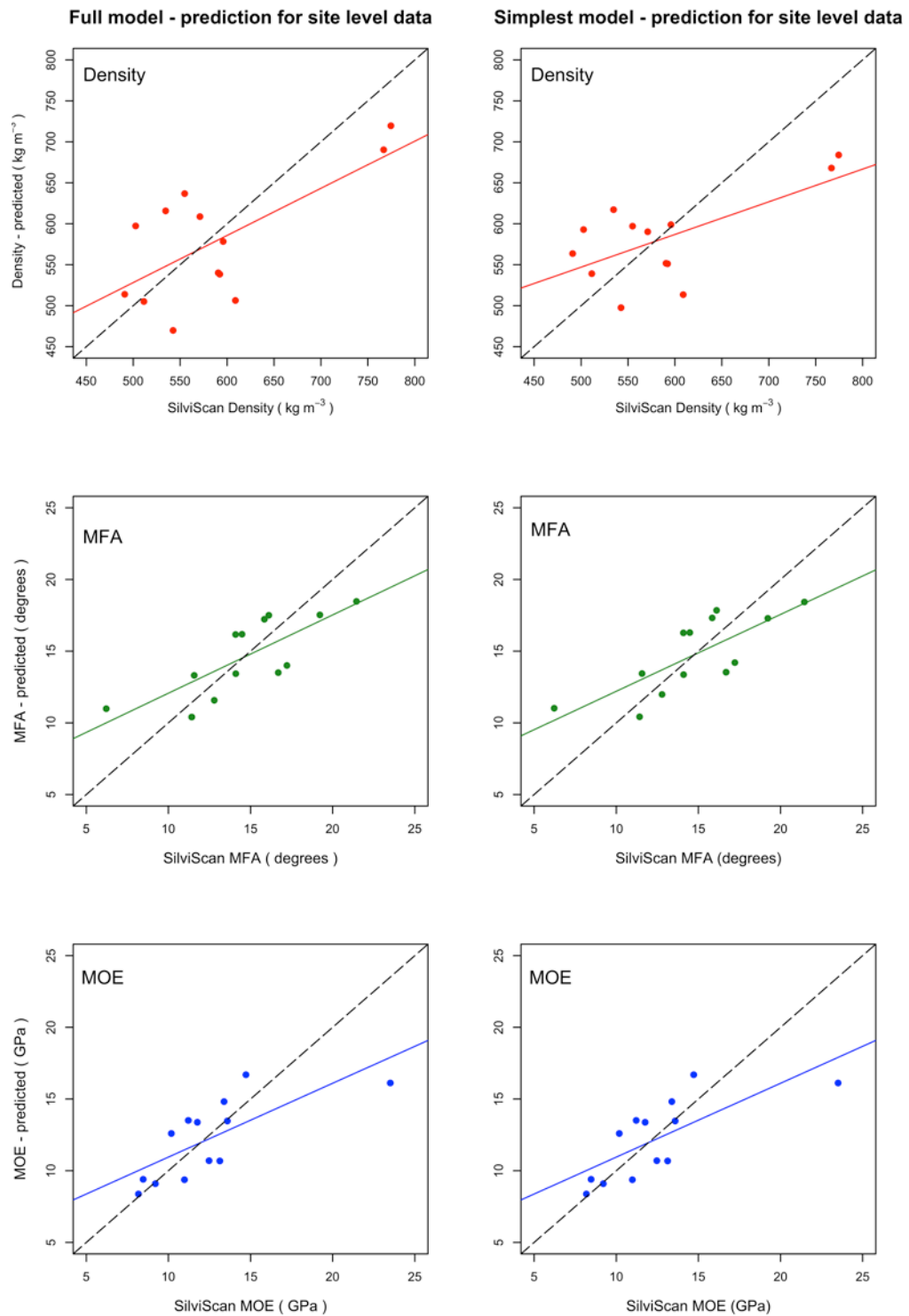


Figure 5.2 Full model (left) and simplest model (right) predictions for density, MFA and MOE in the validation population. The SilviScan measurements are plotted against the predicted site values. The dashed line represents a 1:1 relationship and the solid line shows the fitted linear regression (R^2 values are given in Table 5.4) and all models are significantly different from slopes of zero ($p < 0.05$). MOE_d plots are the same because the full model was also the simplest model. Note that these models refer to wood properties measured at breast-height (1.3 m above ground level).

5.3.3 Spatial predictions

The spatial mapping of wood properties across Tasmania was undertaken using the final simplest models of density (Figure 5.3), MFA (Figure 5.4) and MOE_d (Figure 5.5). These three maps were initially modeled for plantations of age ten years and limited ('clipped') by the ranges of Elevation and Annual Precipitation values used to develop the models, i.e. Elevation between 74m and 875 m asl, and Annual Precipitation between of 715 and 1685 mm. In addition all reserve areas listed under the National Parks and Reserved Land Management Act 2002 were excluded.

The final simplest density model included Annual Precipitation and Elevation, both of which had significant negative effects. In general, precipitation increases from north to south and east to west in Tasmania, and with increasing elevation. Consequently, lower density *E. nitens* plantation were predicted to be concentrated in higher elevation areas, principally in the north of the island and on the edges of the Central Plateau. The mountain range close to Devonport in the north-west and around Scottsdale east of Launceston have the largest area of lower density. Conversely, the northern Midlands were predicted to yield higher density *E. nitens* wood.

The general distribution predicted of MFA and MOE_d values follow trends in Annual Precipitation but their values were in the opposite direction. In other words, where Annual Precipitation increased, predicted MFA values increased and MOE_d values decreased. Plantations in north-western Tasmania and its mountains, therefore, were predicted to have lower MOE_d values and higher MFA values, whereas MOE_d values were predicted to be higher and MFA lower around the more central Midlands region as a consequence of the lower precipitation, which characterises this part of the island. The southern areas of Tasmania had intermediate-high values of predicted MOE_d with values from 10.9 to 13.0 GPa, and intermediate-low values of MFA from 13.9 to 16.1 degrees.

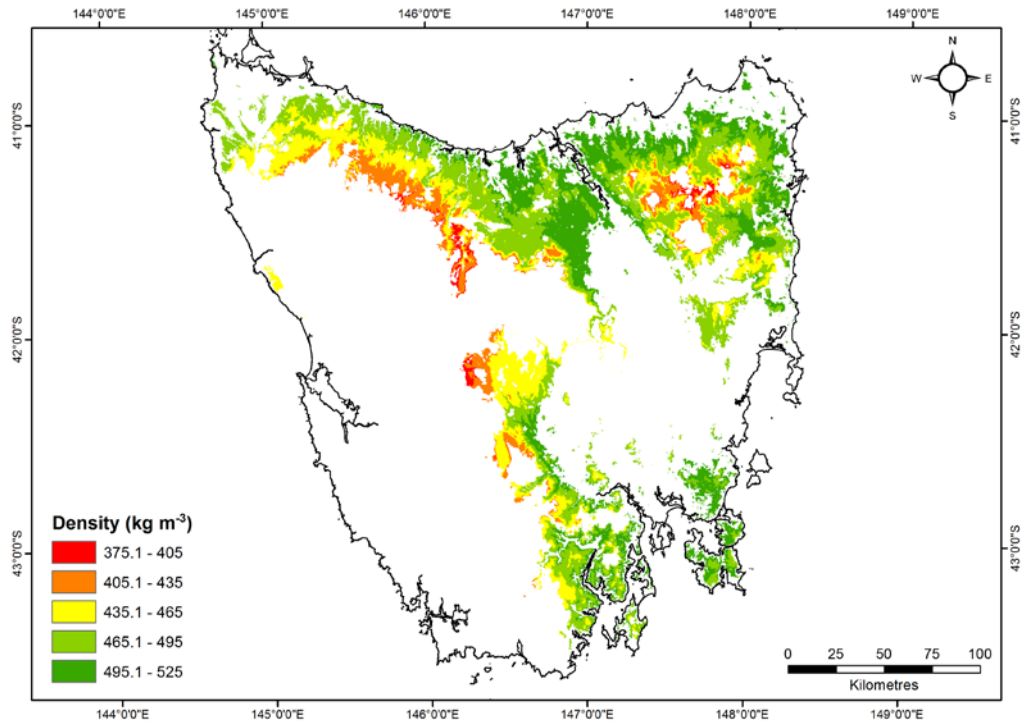


Figure 5.3 Predicted spatial distribution of density across Tasmania for 10-year-old *E. nitens* plantations as assessed at 1.3 m above ground level. The surface has been clipped according to the data of the samples in the training data set, which cover 74 to 875 m asl elevation and an annual precipitation range of 715 to 1685 mm. In addition, all reserves areas listed under the National Parks and Reserved Land Management Act 2002 have been excluded.

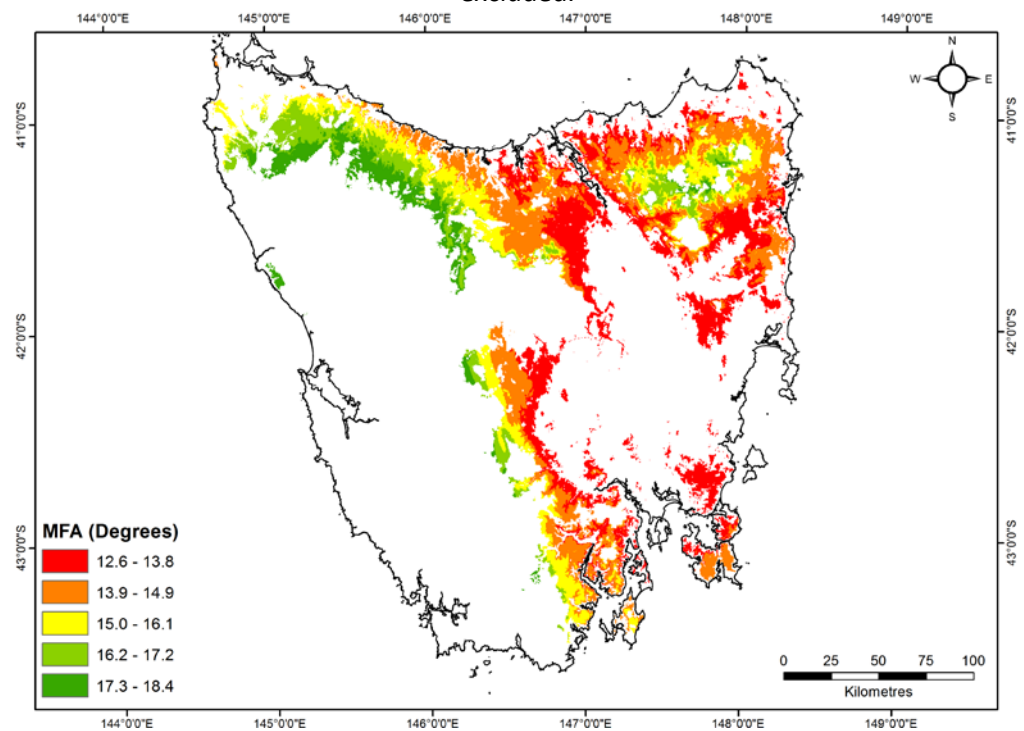


Figure 5.4 Predicted spatial distribution of microfibril angle (MFA) across Tasmania for 10-year-old *E. nitens* plantation as assessed at 1.3 m above ground level. The surface has been clipped as indicated in Figure 5.3.

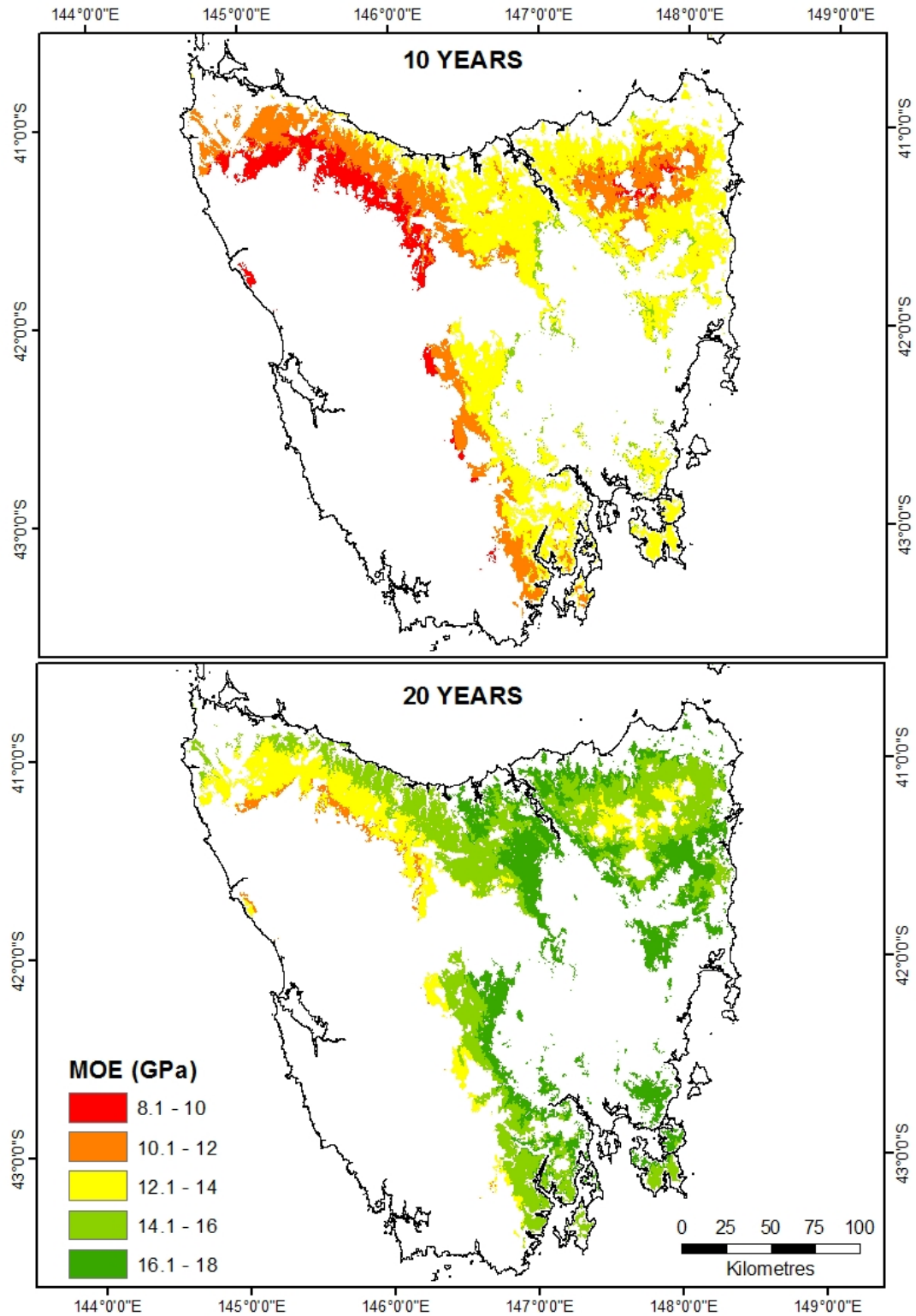


Figure 5.5 Predicted spatial distribution of modulus of elasticity (MOE_d) across Tasmania for 10 year (top) and 20 year (bottom) old *E. nitens* plantation as assessed at 1.3 m above ground level. The surface has been clipped as indicated in Figure 5.3. Values in green indicate areas where the resource is predicted to exceed the 14 GPa MOE_d values. The maps clearly show how the weighted tree mean MOE_d increases with plantation age.

5.4 Discussion

In the current study, multiple linear models were developed to identify which forest, environmental and climatic variables were relevant to predict the spatial distribution of density, MFA and MOE_d across the island of Tasmania in Australia. When each group of predictor variables (i.e. forest, environmental and Climate) was considered independently, multiple variables were found to significantly influence wood properties. When all variable selected from these groups were considered simultaneously, however, the final simplest models included only Plantation Age, Annual Precipitation (for all three wood properties), and Elevation which was only included in the density model.

Although only two variables were significant in the final models, a discussion by groups permits the evaluation of the rest of the variables with respect to their trends and interactions with density, MFA and MOE_d in a clear and simple manner. Among the forest variables, the Mean Height of Dominant Trees was retained as a significant variable in both the full and simplest models for all wood properties, while Tree Diameter also had a significant effect on MFA. The Mean Height of Dominant Trees would be associated with the proportion of mature/juvenile wood (Zobel and Sprague 1998). The use of this variable reduces the variability among trees, so the relation between mean wood properties and site would be clearer than the other forest variables evaluated here. This has connotations for forest managers, as the use of this variable would replace the need to know the age of the site to estimate wood properties. The positive influence of Tree Diameter on MFA reflects a positive relation between MFA and growth rate. In one of the few studies found on regional modelling of MFA, Moore *et al.* (2014) found that increased growth rate created wider rings resulting in slightly higher MFA values, when modelling the regional variation of MFA in *Pinus radiata* across New Zealand. It was not possible to corroborate or refute this result for *Eucalyptus* as information about modelling regional wood properties in hardwoods could not be found. However, caution must be taken in transferring results from softwoods to hardwoods. Tension wood, growth rate and density can be interrelated in *E. globulus* (Washusen *et al.* 2001). However, it is unlikely the association between tree diameter and MFA

observe is due to tension wood as processing studies have revealed no association between the presence of tension wood and MFA in *E. globulus* and low levels of damaging tension wood in *E. nitens* (Washusen 2011). However, this result would not be a consequence of probably presence of tension wood in the sample because according (Washusen *et al.* 2001) it is not possible to positive correlated tension wood with MFA in *E. globulus*.

Among the environmental variables, Elevation had a significant effect on the three wood properties evaluated: increased elevation was associated with decreased density, decreased MOE_d and increased MFA. Elevation in Tasmania is associated with decreasing temperature and increasing rainfall. While there is plenty of evidence from previous studies to link higher rainfall (and therefore water availability) to changes in wood properties (as discussed in Section 4.2.3.2), there is not an established unique direct link between temperature and wood properties in *Eucalyptus* (discussed further below).

Climatic variables associated with precipitation and temperature affected the wood properties in different ways. In the full model, density was affected simultaneously by both temperature and precipitation variables, with positive and negative influence, respectively. On the other hand, MFA and MOE_d were only affected by precipitation variables in the full model, with a positive effect on MFA and negative effect on MOE_d. The simplest model revealed that Annual Precipitation was the only significant variable across models of density, MFA and MOE_d, and Annual Mean Temperature was included in the density model only. The significance of precipitation variables is consistent with previous research (Drew *et al.* 2009; Wimmer *et al.* 2002b). Precipitation variables affect the soil water availability (Almeida and Sands 2015), which is known to have a strong relationship with wood properties at all measurement scales, from the cellular level through seasonal and annual growth to tree, site and regional levels as discussed in Section 5.1.1. As discussed in this section and shown by the present results, increased water availability leads to a decrease in density and MOE_d and increase in MFA values.

The positive relationship between temperature variables and density, on the other hand, is unexpected. As stated previously, there is little evidence from previous studies to suggest a strong and unique link between temperature and density in *Eucalyptus*, though a positive relationship has been demonstrated in species such as *Pinus radiata* (Beets *et al.* 2007; Palmer *et al.* 2013; Watt *et al.* 2008). This is probably because temperature is generally highly correlated with other variables such as precipitation and elevation, making it difficult to clearly establish the effect of temperature alone. A causal link is also difficult to establish: although the growth rate of *E. nitens* has been shown to increase with warmer temperatures (Downes *et al.* 1999), it is recognized as a cold-tolerant species (Wardlaw 2011) and Downes *et al.* (2006) showed that growth rate had no effect on wood density in *E. nitens* and *E. globulus* when provenance, soil water conditions and site characteristics were held constant. In this study, there was a strong correlation between temperature variables and other variables including elevation, which were revealed during development of the final full model, which considered all selected variables from the groups simultaneously. For this reason, temperature variables were not included in the final simplified model in favour of Elevation.

Finally, the substitution of more readily understandable variables in the simplest models generally had a minimal effect on model fit and predictive power (R^2 and AIC values). It is therefore considered that this substitution was justified given the increased ease of interpretation and implementation of the models in an industry context. For density, substitution of Elevation for the Maximum Temperature of Warmest Week variable decreased the model fit (R^2) by 8% and increased the AIC values by 8.6. This was due to the fact that this variable directly influences density, as noted previously by Downes *et al.* (1999) and Downes and Drew (2008), whereas Elevation only explained a part of the variation of density. For MFA, the simplest model had the same coefficient of determination, and slightly higher AIC value when compared with the full model. This is because the full model variables were related with precipitation, so when they were replaced by Annual Precipitation it adequately explained the variability of MFA across sites. In the case of MOE the

final full model only considered Annual Precipitation so the full and simplest models were equivalent.

Although the validation of both full and simplest models showed lower coefficients of determination (R^2) than the original models, their values ranged from 43 to 59.7% which is similar in predictive power to other validated models developed for the resource characterisation of wood properties using SilviScan methodology and similar modelling methodology. For example Lessard *et al.* (2014) obtained R^2 values of 51 and 33% for density, and 59 and 48% for MOE_d in models of black spruce and balsam fir, respectively. For MFA, Auty *et al.* (2013) developed a model for Scots pine that explained 63.4% of variation of this wood property, only 4% better than the present results. With cheaper technologies and traits such as wood density which allow greater sampling intensity (both within and across sites), higher model validations R^2 have been achieved, as for example the 70% reported for outerwood density across the *Pinus radiata* estate in New Zealand (Palmer *et al.* 2013). Although, the prediction capacity of the current and other models is relatively low, according to Lessard *et al.* (2014) the regional models developed could be useful to make a spatial prediction of wood properties in regions with wide gradients of geography and climate, as is the case in Tasmania.

In the present study, the number and diversity of sites used in the validation would influence the results. With more sites across a greater geographic range (therefore including a greater degree of variation in predictive variables) it is possible that stronger validations and more robust estimation of the site level properties may have been obtained. For example, two models for MOE_d and density, experienced problems due to one or two sites with high leverage which had a large influence on slope. The spatial representation of wood property variation through Tasmania is therefore capable of showing the broad spatial influence of climatic and environmental variables, particularly Annual Precipitation and Elevation. The other possibility for model improvement includes, increasing the number of trees sampled per site to better estimate site means. For example, Kimberley *et al.*

(2015) used 10-30 trees per site in their study of site variation in wood density of *Pinus radiata* in New Zealand. However, in our case as we were particularly interested in MOE and MFA, their high costs of measurement restricted sampling. Given the limited resources available it was considered better to maximise the number of sites studies in order to obtain a more robust model. Nevertheless one of the options of improving the predictive power of these models, is to increase the number of trees used to obtain a site mean, which is particularly feasible for wood density. The other point to note is that the validation R^2 may be improved with better continuity and range of sites relative to those used to develop model. This issue may explain the greater reduction in R^2 between the original and validation models for Density and MOE in particular.

The relevance of these models characterising wood properties of forestry plantations for forest managers and mill owners is readily evident, due to their potential for optimising wood utilisation and production efficiencies. Wood property characteristics, however, are only one of many factors to consider when optimising the economic outcomes of forest operations. For example, our study shows that lack of rainfall has a beneficial effect on wood properties, however this same characteristic usually results in lower growth rates and site productivity (Almeida and Sands 2015).

Thus, to fully evaluate forest plantation characteristics for economic solid-wood production, quantitative information on both external (e.g. tree volume) and internal tree characteristics (wood properties) are required. An alternative to do this, it is develop complementary models using airborne LiDAR Data, with the purpose to improve the ability to predict wood properties in a more fine scale (Luther *et al.* 2013). Consequently, modelling systems which can incorporate such information would therefore allow managers to better balance the competing requirements for high, or at least reasonable, growth rates and optimal wood characteristics (Burkhart and Tomé 2012).

Chapter 6 Discussion and conclusions

There is an increased need for efficiency in the world forestry industry in order to maximise the potential of available resources in the face of rising costs, decreasing land area and demands for sustainability and a diverse range of end products. In this context, the maximisation of returns from existing and future resources will be critical. This thesis has examined issues relevant to the improved use of the Tasmanian *E. nitens* resource. *Eucalyptus nitens* plantations comprise 88.4% of Tasmanian hardwood temperate plantations, which in turn account for 24.2% of Australian hardwood plantation resources (Gavran 2014). Veneer processing has been proposed as a use for this resource (Blakemore *et al.* 2010; McGavin *et al.* 2014b).

According to Shi and Walker Shi (2006), veneers are used in multiple different end products, with varying requirements for appearance and structural properties. As such, maximising the volume and economic value of veneer products produced from *E. nitens* plantations will be contingent on: a) the availability of raw materials, b) efficiency of production processes, and c) the value and demand for specific end products. This thesis has focussed on issues relevant to improving resource utilisation with regards to the first two of these factors.

6.1 Processing the *E. nitens* resource.

The ability to add value and minimise loss of the raw material throughout the supply chain is of direct relevance to the forestry industry. The post-harvest processing phase is important as changes in the way in which raw material is managed at this stage can affect the expression of defects and therefore the quality and recovery of end products.

Log storage

One of the major sources of defects and loss of raw material in *Eucalyptus* is log-end splitting, caused by the release of growth stress (Archer 1987; Kubler 1988). Storage is a key phase in the processing of logs for timber or veneer and various approaches have been adopted by processors to minimize log-end splitting during this period. Such approaches include the application of a log-end sealer, the use of sprinklers in log yards to keep logs moist, and debarking just after steaming and peeling (Chauhan *et al.* 2006b). From a forest point of view, studies of the effects of silviculture or genetics on the magnitude of growth stress have been undertaken to try control/minimize the negative effect of growth stress (Kubler 1987). However, as consequence of multiple factor affecting the growth stress, there is no clear consensus over the best way to control it in the forest (Kubler 1988). Nevertheless, in *E. nitens* there is significant genetic variation in this trait with a high heritability, reported particularly for upper log-end splitting (Blackburn *et al.* 2011), suggesting that there is opportunity for genetic improvement.. The results of Chapter 2 show that log-end splitting occurs in two phases, with split development most rapid between harvesting and arriving at the log yard (13-14 days), and slower once at the log-yard and after steaming (12-19 days). This finding is consistent with other eucalypt studies (Bariska 1992; Priest *et al.* 1982). In the experimental system used, there was no significant effect of steam treatment on split development. However, there was large (up to 39%) variation in splitting among logs from different sites, and although splitting was initially similar between lower and upper logs, it became greater in the upper log with increasing storage time. This may be due to higher, longer-lasting compression forces on wood higher up the tree stem, which would then potentially require more time to release (Kubler 1987).

These results show that storage time can have a large impact on the degree of log-end splitting. The relationship presented in this paper therefore not only suggests that managers should minimise storage time wherever possible, but that the critical time for split development is during the first phases of processing and therefore additional care should be taken during these times. Additionally, upper logs should

be processed before lower logs as they develop splits at a higher rate in storage. Future research should be able to predict the percentage of the raw material which will be lost to splitting under different storage scenarios, allowing them to better predict economic outcomes in response to market forces.

The results of Chapter 2 also indicate that it is possible to adequately quantify log-end splitting through assessing the maximum split length on the log surface. Although this method does not have the same level of detail as the Split index (SI-2), the results of this thesis show that there is a strong relationship between the two measures and the maximum split length is more readily measured and allows for assessment of the change in log-end splitting during log processing for veneer.

Determining the volume of wood with defined structural properties

As discussed in Chapter 1, veneer is used in a wide range of end products with different requirements for appearance and structural properties (Forest Products Laboratory 2010; Moore and Cown 2015b). As such, although wood properties vary within and among trees, sites and regions, it should be theoretically possible to maximise the value and overall yield of commercially useful end products through the allocation of raw material to appropriate manufacturing processes based on the wood properties and the demand for particular end products. This optimisation, however, is contingent on an understanding of how wood properties vary in the harvested resource (Lundqvist *et al.* 2009).

While predictions of average wood properties for a tree give only general information about potential veneer recovery of a given quality, radial profile models (quantifying how these wood properties vary through of the stem) permit more accurate estimation of potential veneer recovery by estimating the volume of veneers with a specific mechanical grading, based on wood properties such as MOE_d (Leban and Haines 1999). The aim of Chapter 4, therefore, was to develop radial models to predict the proportion of wood within harvested logs with MOE_d above a predefined threshold value (14 GPa) as an indicator of suitability for use in structural products.

The results of Chapter 4 showed that a three-parameter logistic function best fitted the variation of MOE_d and revealed marked differences between inner- and outer wood in *E. nitens*. These differences are consistent with those observed in other *Eucalyptus* species (Downes *et al.* 2014; Lima *et al.* 2004).

The model, developed with data at 2.5 m height, permitted prediction of the maximum proportion of the tree volume above the 14 GPa threshold, considering the increase of corewood with the tree height.

At harvest, 85% of the wood from the Strathblane plantation was above the 14 GPa threshold compared with 70% and 64% for Geeveston and Florentine respectively. The low productivity Strathblane site reached this threshold more than 2 and 3 years earlier than the Geeveston and Florentine sites respectively.

The results of Chapter 4 also indicate that it is possible to substitute percent of area (size) measurements for the more traditionally used cambial age, as model results were equivalent using either explanatory variable. Cambial age measurements require the measurement of ring boundaries, which is extremely time consuming but also susceptible to error in *Eucalyptus* species which are prone to the development of false rings (Hudson *et al.* 1998). Using percent area as the independent variable gives the opportunity to evaluate the economic implications of silviculture and growing conditions more easily, quickly and accurately as it is directly related to wood volume. It is thus easier to use when defining the best processing strategies according to the targeted final products, and ultimately to define the value of logs and forests (McGavin *et al.* 2015).

Peeling and veneer recovery

As discussed in Chapter 1, three collaborative studies were conducted in parallel to this thesis, which studied the impact of different sites, silvicultural treatments and processing techniques on the recovery of veneer products (Hamilton *et al.* 2014; McGavin *et al.* 2014a; McGavin *et al.* 2014b). These studies are included in Appendix B. All three of these studies indicate that veneer processing is highly

applicable to the *E. nitens* resource, with commercially acceptable recovery of veneers albeit of generally medium-low grade (Hamilton *et al.* 2014; McGavin *et al.* 2014a; McGavin *et al.* 2014b). They do, however, indicate strong site effects, and in one case, effects of stem position, on the recovery rate of veneers (Hamilton *et al.* 2014; McGavin *et al.* 2014a; McGavin *et al.* 2014b).

These differences in recovery were observed after removal of the log end-splits reported in Chapter 2 by post-docking peeling of logs. The subsequent site differences were not the same of those evident for log end splitting, suggesting that site has multiple independent effects. Log end splitting is therefore not the only factor which would affect green recovery from harvested logs and its effect can be minimised when there is the opportunity for docking prior to peeling (Hamilton *et al.* 2014).

In summary, the studies presented in Chapters 2 and 4 and Appendix B indicate that there opportunities to increase the volume, quality and value of veneer at different stages of the production process. These methods and results are likely to have wider applicability, such as to other *Eucalyptus* plantation species.

The strong site effects observed in all studies referred to here, however, indicate that a large proportion of the variation in wood properties, splitting and recovery rates is likely to be driven by environmental or other site-related factors. A more detailed understanding of the influence of these factors on the variation of wood properties is therefore an important step in effectively maximising the potential of the *E. nitens* resource for veneer processing.

6.2 Assessment of the *E. nitens* resource

In order to understand and predict the variation in density, microfibril angle and modulus of elasticity at regional, site, tree and intra-tree scales, an accurate method for measuring of these properties is required. As discussed in Section 1.3.2.1 of the Introduction, traditional methods are labour intensive and involve destructive sampling. SilviScan, a reliable technique which has been specifically developed for

the non-destructive measuring of radial variation in wood properties (Downes *et al.* 1997), is nevertheless expensive restricting its use for very large datasets (Giroud *et al.* 2015). The aim of Chapter 3, therefore, was to develop NIR calibrations as an alternative, more affordable method to predict density, MFA and MOE_d at different scales in Tasmanian *E. nitens*. While the ability of NIR to predict Kraft pulp yield in eucalypts at a regional scale has been demonstrated (Downes *et al.* 2010b; Downes *et al.* 2009b), multi-site NIR calibrations for the prediction of density, MFA and MOE_d have not previously been developed for *E. nitens*.

NIR calibration models for density, MFA and MOE_d for *E. nitens* were successfully developed in this study (with an average R² value of 73.2% for density, 66.1% for MFA and 81.2% for MOE_d), but the capacity of these models to predict wood properties when applied to independent sites was mixed and generally poor. The best predictions accounted for 54%, 64% and 46% of the variation in density, MFA and MOE_d, respectively at independent sites. Although previously developed *E. globulus* calibrations showed better performance of NIR calibrations than the current models, these models when applied to *E. nitens* are still not capable of satisfactorily predicting values for independent sites.

The reasons behind this poor performance of the NIR modelling can only be hypothesised (see Chapter 2), but for the purposes of this study, the NIR calibrations did not allow sufficiently accurate prediction of density, MFA and MOE_d values to characterise *E. nitens* plantations at an intra-tree, tree, site and regional scale. For this reason, SilviScan measurements were used throughout Chapters 4 and 5. SilviScan, while less affordable, allows for accurate, precise data collection at very fine scales (Lenz *et al.* 2010a) and thus the development of a very detailed radial profile of wood properties (Medhurst *et al.* 2012; Xu *et al.* 2015). In addition, SilviScan has been extensively used in previous research involving intra-tree, site and regional analyses (Lessard *et al.* 2014; Moore *et al.* 2014; Moore *et al.* 2015).

6.3 Factors affecting resource quality

As can be seen from the previous sections, there is large variation in wood properties between plantation sites, which can significantly influence the recovery rate (Chapter 2) and quality of end-product veneers (Chapter 4). Understanding how these wood properties vary across the plantation estate is therefore essential to be able to optimise the use of available resources (Lessard *et al.* 2014; Malan 2003; Payn *et al.* 2015).

Throughout the thesis, age and environmental factors were identified as strongly affecting wood properties. Of these, age was the strongest and most consistent effect. Within individual trees, all three wood properties varied predictably with increasing cambial age, with density increasing linearly, MOE_d increasing asymptotically and MFA decreasing asymptotically as shown in Chapter 4. Similarly, plantation age was always a significant factor in the regional forest characterisation models developed in Chapter 5, again with increased average density and MOE_d and decreased MFA in older plantation sites.

Site also had significant effects on wood properties both within trees and across plantation sites (Chapter 4). A significant site effect was detected in models of radial variation of wood properties within individual trees, suggesting a role of the environment or silviculture. These site effects did not change the nature of the radial relationship, but did influence the magnitude of variation across the radial profile. Similarly, the incidence of log-splitting (Chapter 2) and the rate of recovery of veneer products (Hamilton *et al.* 2014; McGavin *et al.* 2014a) varied significantly among different plantation sites. In the regional forest characterisation models (Chapter 5), although plantation age had the highest predictive power of any explanatory variable, annual precipitation was also found to be a significant environmental predictor of all wood properties, while elevation was significant in models of density.

These results are in accordance with other empirical studies, which have demonstrated relationships between various factors, particularly age and water availability, and wood properties (see Section 5.1.1). It is also recognised that wood properties change in response to environmental factors via underlying physiological responses in the cambial zone (Larson 1994). These responses are contingent on a complex and co-varying array of factors and are therefore often difficult to generalise (Drew *et al.* 2009). Broadly speaking, however, according to Drew *et al.* (2009), when the processes of cell expansion and wall thickening are limited by water availability or other environmental factors, properties such as wood density and MFA may be markedly altered.

Obviously, a broad range of environmental factors and underlying mechanisms are likely to be interacting to give the observed range of wood property values observed in this thesis. The focus of this thesis, however, was not on the exact mechanisms driving these relationships through process-based models but rather the development of predictive models based on easily measurable properties for use in management and development of forest resources (Chapter 5).

In Chapter 4, we developed models of radial variation in wood properties, helping to more accurately quantify these properties at the level of individual trees and sites. As discussed in Section 6.1, these models are potentially of great use in managing the available resources as well as planning future work, by enabling prediction of the volume of wood available with specific wood properties as required for targeted end products. In addition, these models revealed significant variation of MFA and MOEd through the stem radius, with high variation close to the pith and more stable properties close the cambium. Although, it was outside of scope of this thesis, with additional resource and time, the finding of this thesis study indicates that it should be possible to identify the impact of rotation age and the transition age of *E. nitens* where wood properties stabilise. This will assist managers by indicating the minimum age or size at which trees will start to produce wood of required quality for structural applications.

The forest characterisation models developed in Chapter 5 are directly relevant to the forest industry. These models showed that it is possible to represent the variability of wood properties of interest based on easily accessible variables such as annual precipitation, elevation and plantation age. These predictive models have been used to map the spatial variation in these key wood properties across a plantation estate in Tasmania, which makes the patterns of variation more readily understood and visualised. Such an approach allows for better characterisation of the available resources with respect to the specific requirements of the end products. Coupled to models of tree growth and productivity, these models have potential to allow better evaluation of the economic potential of *E. nitens* plantations across Tasmania. In addition, they provide a template for the development of similar models for other geographic regions where *E. nitens* is planted or for *Eucalyptus* species plantations in general.

6.4 Conclusions

In conclusion, this thesis examined the opportunities for improving the use of the Tasmanian *E. nitens* plantations for veneer, by understanding which factors are crucial to improve the veneer recovery and optimise use the forest resource. The key finding of these studies was that different sites and the associated environmental factors are responsible for a large proportion of the variation in the *E. nitens* resource in Tasmania. This has consequences for veneer recovery, as it influences the magnitude of log-end splitting, independent of pre-peeling processes. Site, tree age and environmental variables also drive variation in density, microfibril angle and modulus of elasticity, three wood properties which are crucial in veneer production. These effects were noted at intra-tree, inter-tree, inter-site and regional scales. This study showed that it is possible to characterise and predict this variation in wood properties across the region based on easily measurable variables (plantation age, site elevation and annual precipitation).

These findings are highly applicable to the effective management of *E. nitens* plantations, as these wood properties determine the range of possible end products

and therefore the end value of the veneer produced. Alongside information on growth rate and productivity at these sites, these models and spatial representations may therefore allow managers to predict and maximise economic returns from the available resources. While these models have been developed for Tasmanian *E. nitens*, the methodology is widely applicable and future research would allow the development of similar tools for other regions or plantation species.

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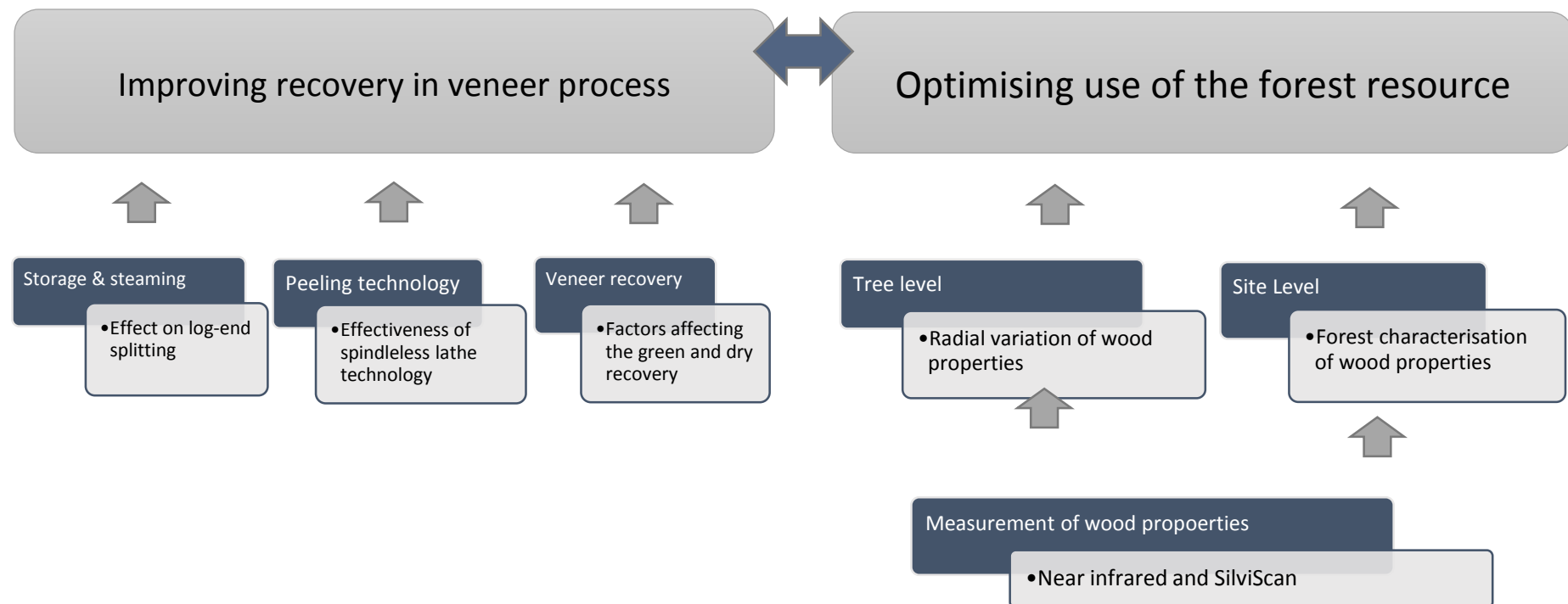
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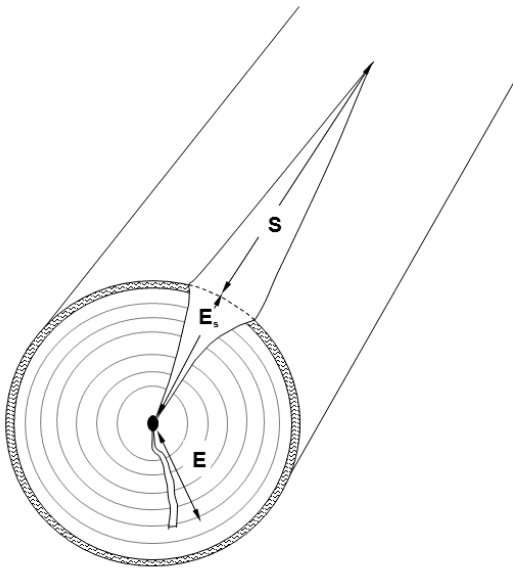
Appendix A

Diagram of the studies of this thesis



Appendix B

Illustration of calculating of Split Index 2 (SI-2)



Split type 1 is a split circumscribed on the log end = $\left(\frac{E^2}{2}\right)$

*Split type 2 is a split on the end and propagated along the log surface = $\frac{(S * E_s)}{R^2}$*

Split index 2 of the log is calculated as sum of all single split type 1 and 2 from both log ends.

Appendix C

Summary of wood properties by site

Table C. 1 Summary of wood properties measured using SilviScan by site. All data are weighted by area of disk and based on individual tree data.

Statistics	Density			MFA			MOE _d		
	Strathblane	Geeveston	Florentine	Strathblane	Geeveston	Florentine	Strathblane	Geeveston	Florentine
n	21	10	9	21	10	9	21	10	9
mean	603.4	600.5	557.7	11.4	12.8	12.6	14.9	14	13.6
se	8	13.5	9.1	0.3	0.5	0.5	0.3	0.4	0.4
sd	36.9	42.8	27.3	1.4	1.5	1.5	1.4	1.3	1.3
median	597.8	587.5	556.7	11.4	12.4	13	15	14	13.5
min	540	540	515.1	8.8	11.2	10.2	12.9	12	11.9
max	685.8	683.5	604.6	13.6	15.1	14.7	18.2	15.9	16.1
range	145.8	143.5	89.5	4.7	3.9	4.4	5.3	4	4.2

Table C. 2 Summary of wood properties measured using SilviScan by site. All data are unweighted (core means) and based on individual tree data.

Statistics	Density			MFA			MOE _d		
	Strathblane	Geeveston	Florentine	Strathblane	Geeveston	Florentine	Strathblane	Geeveston	Florentine
n	21	10	9	21	10	9	21	10	9
mean	619.2	634.1	577.1	8.8	9.9	9.8	16.9	16.6	15.9
se	8.2	17.5	11.5	0.3	0.5	0.5	0.4	0.6	0.6
sd	37.8	55.4	34.5	1.5	1.6	1.6	1.7	2	1.8
median	621.7	622.1	575.1	8.8	9.9	10.4	17.3	16.4	15.4
min	554.2	556	537.5	6.2	8.1	7.4	14.6	14.2	14.4
max	700.1	741.7	651	11.8	12.9	11.4	20.7	20	20.2
range	145.9	185.7	113.5	5.6	4.8	4	6.1	5.8	5.8

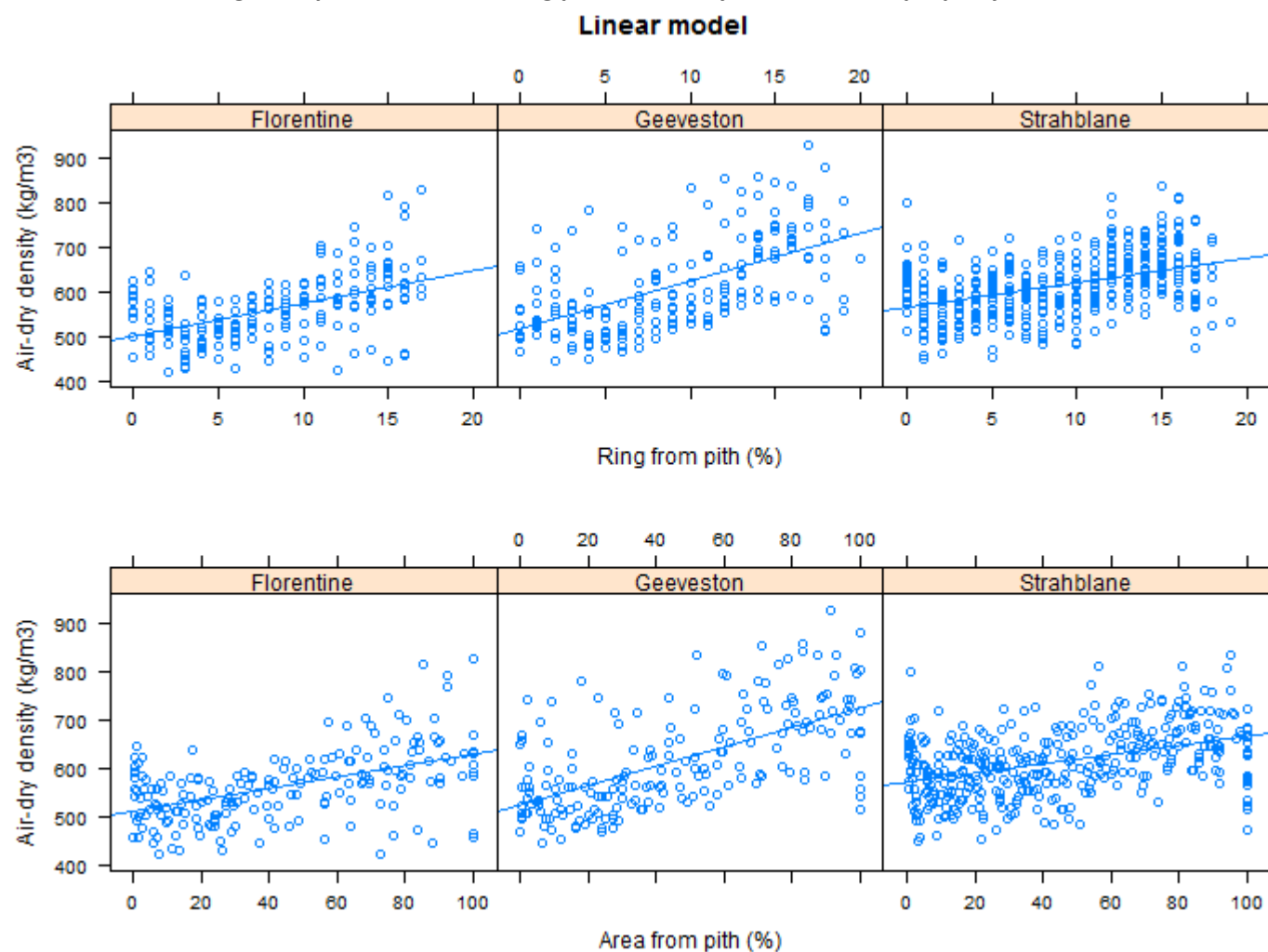
Selection of models

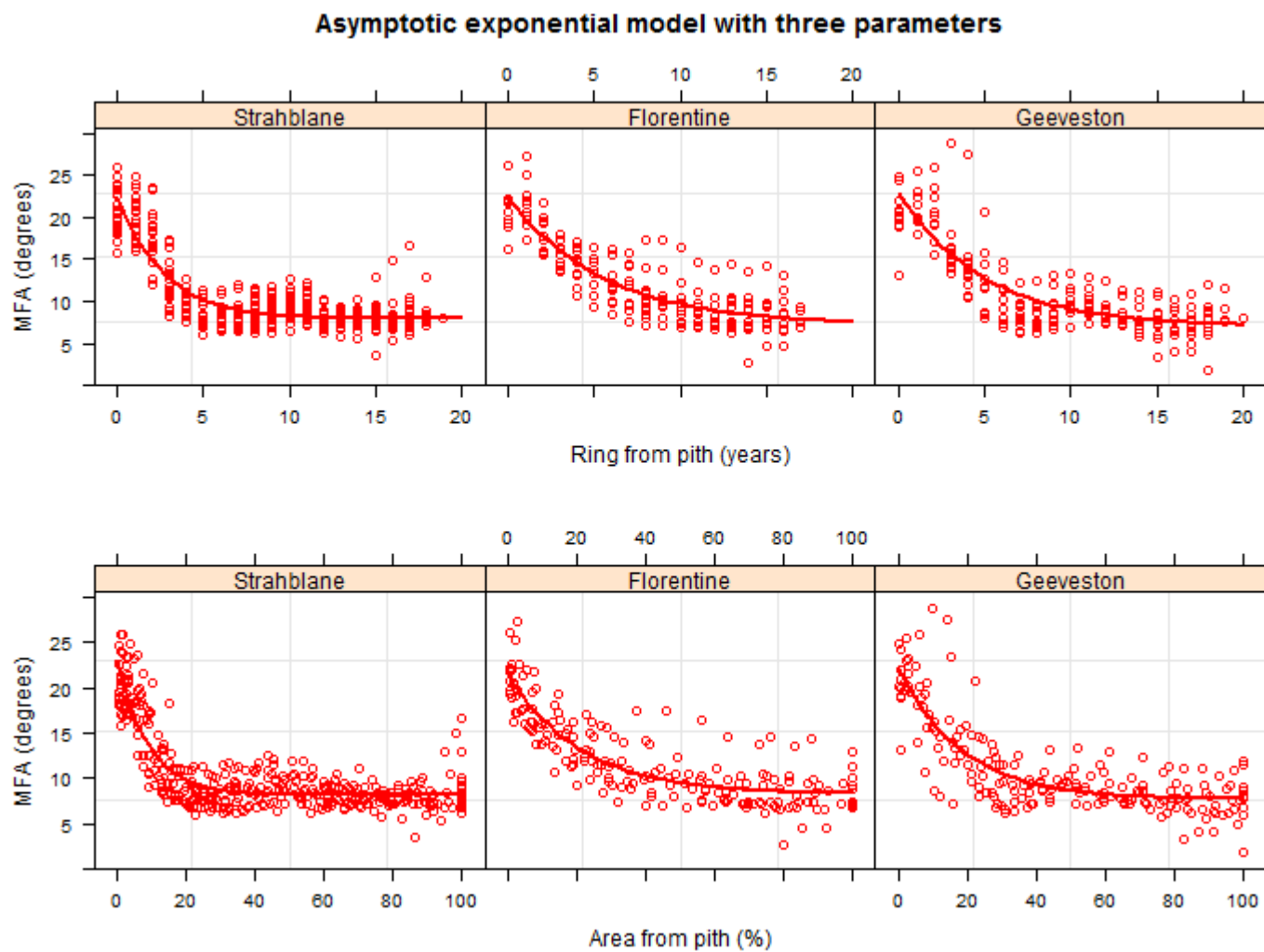
Table C. 3 Akaike Information Criterion (AIC) values for 8 models tested for cambial age and percent of area using pooled data by site and wood property.

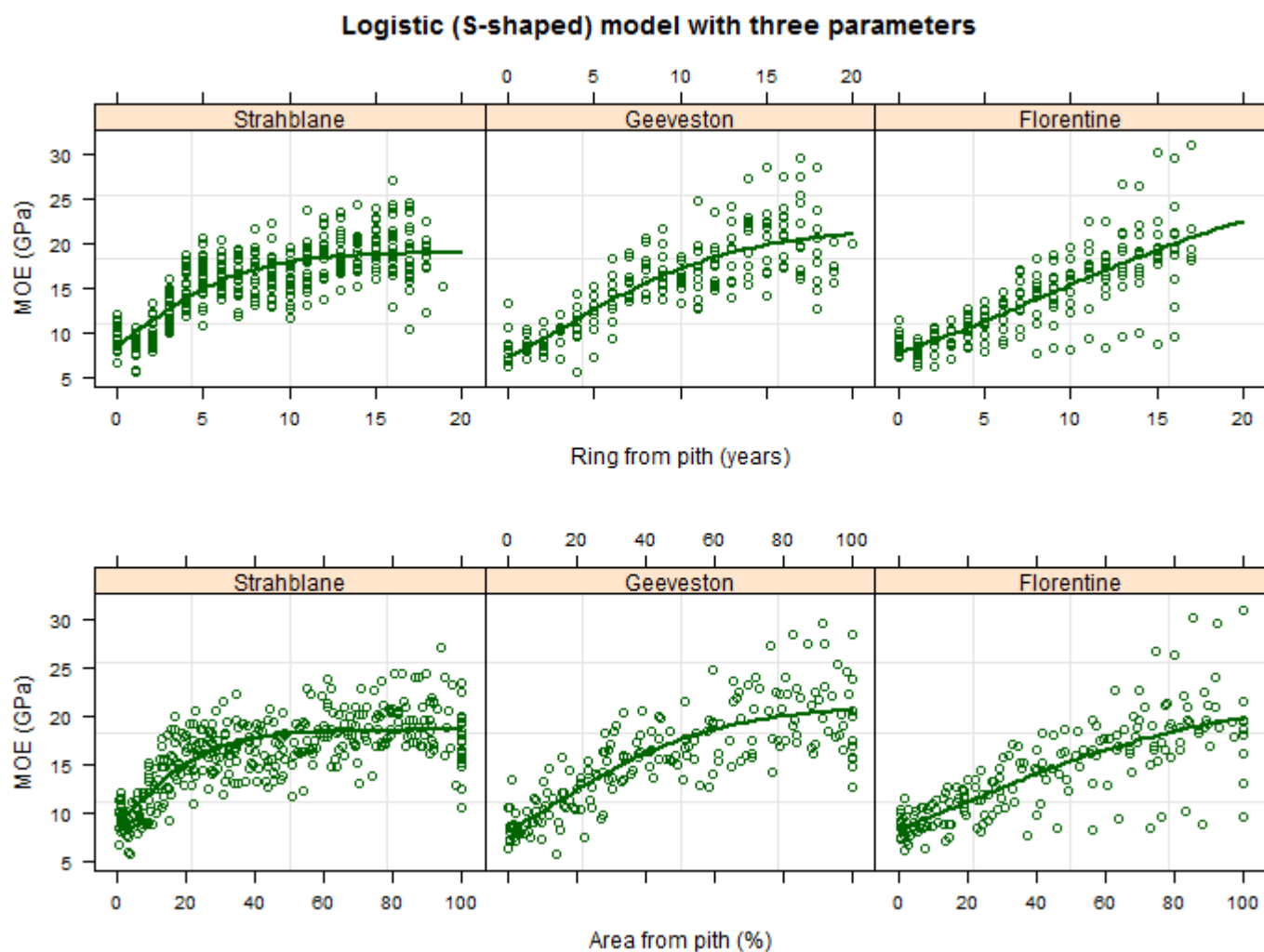
Models	Density			MFA			MOE _d		
	Strathblane	Geeveston	Florentine	Strathblane	Geeveston	Florentine	Strathblane	Geeveston	Florentine
Cambial age									
Lm	4312	2292	2183	2042	1046	976	1865	995	986
Asym	-	-	-	1708	963	906	1781	981	-
AsympOff	-	-	-	-	-	-	1781	981	-
Logis 3	-	-	-	-	-	-	1778	976	987
Logis 4	-	-	2175	-	937	906	1780	976	988
Weibull	-	-	-	-	-	-	-	-	-
Gompert	-	-	-	1727	967	907	1779	978	987
Mic Men	-	-	-	-	-	-	-	-	-
Percent of area									
Lm	4313	2277	2180	2100	1070	1013	1922	1001	997
Asym	-	-	-	1699	971	916	1796	977	995
AsympOff	-	-	-	-	-	-	1796	977	995
Logis 3	-	-	-	-	-	-	1800	975	994
Logis 4	4295	2269	2175	-	-	-	-	977	996
Weibull	-	-	-	1640	-	915	1798	-	-
Gompert	-	-	-	1714	973	-	1798	976	994
Mic Men	4388	-	2229	2211	-	1156	1946	-	1099

Lm: Linear models; Asym: Asymptotic exponential model; AsymOff: Asymptotic exponential model with offset; Logis 3: Sigmoid function with three parameters; Logis 4: Sigmoid function with four parameters; Weibull: Weibull growth function with four parameters; Gompert: Gompertz function with three parameters; Mic Men: Michealis-Menten model with two parameters. Note: Green highlight denotes selected model and (-) indicates that models did not converge

Figures of selected models for cambial age and percent of area using pooled data by site and wood property.







Appendix D

Additional papers co-authored during the PhD candidature to which the candidate contributed and linked to sampling undertaken for Chapters 2 and 4:

McGavin R, Bailleres H, Lane F, Blackburn D, **Vega M**, Ozarska B (2014b) Veneer recovery analysis of plantation eucalypt species using spindleless lathe technology. *Bioresources* **9**, 613-627

Hamilton M, Blackburn D, McGavin R, Baillères H, **Vega M**, Potts B (2014) affecting log traits and green rotary-peeled veneer recovery from temperate eucalypt plantations. *Annals of Forest Science* **72**, 357-365.

McGavin R, Bailleres H, Hamilton M, Blackburn D, **Vega M**, Ozarska B (2014a) Variation in rotary veneer recovery from Australian plantation *Eucalyptus globulus* and *Eucalyptus nitens*. *Bioresources* **10**, 313-329.

Veneer Recovery Analysis of Plantation Eucalypt Species Using Spindleless Lathe Technology

Robert L. McGavin,^{a,b,*} Henri Bailleres,^b Fred Lane,^b David Blackburn,^c Mario Vega,^c and Barbara Ozarska^a

The Australian hardwood plantation industry is challenged to identify profitable markets for the sale of its wood fibre. The majority of the hardwood plantations already established in Australia have been managed for the production of pulpwood; however, interest exists to identify more profitable and value-added markets. As a consequence of a predominately pulpwood-focused management regime, this plantation resource contains a range of qualities and performance. Identifying alternative processing strategies and products that suit young plantation-grown hardwoods have proved challenging, with low product recoveries and/or unmarketable products as the outcome of many studies. Simple spindleless lathe technology was used to process 918 billets from six commercially important Australian hardwood species. The study has demonstrated that the production of rotary peeled veneer is an effective method for converting plantation hardwood trees. Recovery rates significantly higher than those reported for more traditional processing techniques (e.g., sawmilling) were achieved. Veneer visually graded to industry standards exhibited favourable recoveries suitable for the manufacture of structural products.

Keywords: *Eucalyptus*; Veneer; Rotary veneer; Hardwood; Plantation; Processing; Grade quality; Recovery

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INTRODUCTION

The Australian timber industry, in particular the hardwood forest sector, is undergoing significant change. Much of this change results from reduced availability and/or reduced quality of the native forest resource for commercial harvesting purposes. Significant areas of native hardwood forests across Australia are being progressively withdrawn from commercial harvesting and managed principally for conservation purposes. While these challenges are not new on the global scene, Australian forestry is challenged with an accelerated transition from native forests to plantations.

About 84% of Australia's one million hectares of hardwood plantations has been established and managed for pulpwood production (Gavran 2013). Species selection, tree breeding programs, and plantation management have focused on achieving high pulp yield, targeted density, and maximum volume, which may adversely affect important properties for value-added solid wood products (Bailleres *et al.* 1995a,b; Bailleres *et al.* 1996a,b; Hamilton *et al.* 2010; Blackburn *et al.* 2011). Small areas of scattered

plantations have been established for higher value products, mainly by State Government bodies. As a consequence, the hardwood plantation resource within Australia now consists of several species growing across a variety of climatic conditions and under a variety of management strategies, resulting in a wide range of plantation qualities and performances (Gavran 2013).

Recently, lower than expected product prices have resulted in an interest in higher value market options. This is despite site, species, and genetic selection, along with the lack of silvicultural inputs; for example, pruning and thinning are suboptimal for the production of logs suitable for many high value products.

Excluding high recovery rate processing technologies such as fibreboard or particleboard manufacture, previous processing studies of plantation eucalypt logs have focused mainly on conventional production systems to produce the traditional suite of sawn products (*e.g.*, Washusen 2011; Washusen and Harwood 2011; Blakemore *et al.* 2010a,b; Washusen *et al.* 2009; Leggate *et al.* 2000). This work has shown that difficulties are encountered in processing most of the existing hardwood plantation resources, with persistent problems arising in recovery, drying, stability, durability, and appearance qualities (Washusen *et al.* 2009). The result has been low profitability due to factors such as small log dimensions, high proportions of juvenile wood, growth stresses, and the high presence of knots. For example, Leggate *et al.* (2000) reported grade recoveries for a range of eucalypt species between 8% and 19% of log volume when sawn into commercial flooring products—less than half of what would be expected from mature native forest logs. Furthermore, Blackburn *et al.* (2011), in a sawing study of more than 500 *Eucalyptus nitens* plantation trees that used modern linear sawmilling technology purposely designed to maximise sawn-board recovery, showed that approximately half of the usual percentage recovery was possible.

Recent international advances in small log sawmilling, mainly tailored for the softwood industry, may have some application in the processing of plantation hardwoods. Nevertheless, challenges remain, including the economic impacts of high capital investment, large volume throughput requirements, low recovery of product, and the matching of dimensions and qualities of sawn wood to markets (Washusen 2011; Washusen and Harwood 2011). Other opportunities exist in the use of emerging thin-sawing techniques to produce attractive “overlays” for products such as composite flooring. This allows the unique properties of these hardwoods species, such as hardness and/or high aesthetic appeal, to be maximised. However, high costs of production, low recovery rates, competition from other more easily converted forest resources, and poorly established markets continue to make this approach economically challenging.

Preliminary research (Hopewell *et al.* 2008; McGavin *et al.* 2006) has shown that the conversion of plantation hardwood logs into veneer can yield significantly higher recoveries when compared with sawn timber processing. The resulting veneer is reported to have mechanical properties that are suitable for the manufacture of structural products (*e.g.*, plywood, laminated veneer lumber, *etc.*) in demand from the building industry (Hopewell *et al.* 2008). This processing method is not without challenges. Reliable adhesive performance and suitable technology to process small diameter logs are among a range of issues requiring further investigation.

While some preliminary research on plantation veneers has provided positive and encouraging results (*e.g.*, Hopewell *et al.* 2008 and McGavin *et al.* 2006), they remain reliant on the use of existing local industry-adopted processing and manufacturing technologies, most of which are not designed for or ideally suited to small-diameter fast-

grown plantation hardwoods. New technologies that have emerged in recent years are better suited to this resource, giving the potential for greater recovery and improved quality. In particular, the use of spindleless or centreless veneer lathes has rapidly expanded, primarily for peeling small-diameter forest resources (Arnold *et al.* 2013). This technology was originally developed in the 1980s to further process the large peeler cores produced from spindled lathes. In more recent years, spindleless lathes have been further developed and adopted through many Asian countries for processing billets from very small diameter trees with success. According to Arnold *et al.* (2013), there are more than 5,000 small-scale veneer mills in China dedicated to the processing of young, small-diameter eucalypt logs. However, there are few publications providing detailed information on the veneer quality and recovery from spindleless lathe technology (*e.g.*, Luo *et al.* 2013). To date, there are no published recovery data (including product grade recovery) for the use of this technology in the processing of Australia's plantation resources, which involve different species and climates from those in Asian countries.

Arnold *et al.* (2013) reported that the adoption of this technology dramatically changed China's veneer processing industry because there is no longer the usual prerequisite for large diameter billets. Instead, small diameter logs (small end diameters of 6 cm or less) from plantations as young as 4 to 5 years old can be processed economically to yield high value veneer (Luo *et al.* 2013). A key to China's production success is the a large number of small-scale operations located close to the forest resource, each using equipment with a low capital cost and dependent on the availability of low-cost labor.

Using spindleless veneer lathe technology and best practice commercial processing methods, this study aimed to quantify and report on log and grade recoveries from logs harvested from six commercially important Australian hardwood plantation species grown for pulpwood and sawn timber.

EXPERIMENTAL

Plantation Sampling

Trees were sampled from commercial plantation stands representing the average resource currently available for the industry's use now and in the immediate future. Six of the major commercially important Australian plantation hardwood species were selected. The species included: *Corymbia citriodora* subsp. *variegata* (spotted gum), *Eucalyptus cloeziana* (Gympie messmate), *Eucalyptus dunnii* (Dunn's white gum), *Eucalyptus pellita* (red mahogany), *Eucalyptus nitens* (shining gum), and *Eucalyptus globulus* (southern blue gum) (Table 1). Plantations sampled were established for a range of end products from traditional pulp to high quality solid wood. The diameter at breast height over bark (DBHOB) was measured for the selected trees. Trees were harvested and cross-cut to provide 1.3 m veneer billets. Each billet met the minimum form requirements including straightness (<40 mm sweep), a small end over bark diameter (SEDOB) no less than 120 mm, along with an absence of ramcorns, double leaders, major branches, and visible external injuries. The billets were sampled so that no more than five billets per tree were collected to ensure adequate representation of trees within the study. Table 1 provides a description for each species, age, plantation location, number, and the DBHOB of trees' sampled, and the number of billets included in the study.

Table 1. Plantation Trial Material

Species	Main Traditional Market	Age (years)	Plantation Location	Number of Trees	Average DBHOB * (cm)	Number of Billets
<i>Corymbia citriodora</i> subsp. <i>variegata</i>	Sawn timber	10–12	Urbenville, New South Wales (28°25'S, 152°32'E); Lismore, New South Wales (29°02'S, 153°05'E); and Tingoora, Queensland (26°22'S, 151°48'E).	80	20.6 (2.5)	215
<i>Eucalyptus cloeziana</i>	Sawn timber	12–15	Pomona, Queensland (26°23'S, 152°52'E); and Beerburum, Queensland (26°23'S, 152°52'E).	55	31.9 (6.3)	223
<i>Eucalyptus dunnii</i>	Pulp and fibre	11	Urbenville, New South Wales (28°28'S, 152°35'E)	60	22.9 (3.5)	148
<i>Eucalyptus pellita</i>	Sawn timber	13	Ingham, Queensland (18°40'S, 146°8'E)	38	28.1 (4.3)	130
<i>Eucalyptus nitens</i>	Pulp and fibre	20–22	Strathblane, Tasmania (43°38'S, 146°94'E); Geeveston, Tasmania (43°15'S, 146°84'E); and Florentine, Tasmania (42°66'S, 146°47'E).	41	34.0 (7.4)	82
<i>Eucalyptus globulus</i>	Pulp and fibre	13–16	Deans Marsh, Victoria (38°39'S, 143°92'E); Orford, Victoria (38°21'S, 142°07'E); and Mumbannar, Victoria (37°96'S, 141°22'E).	60	30.6 (3.7)	120

* Standard deviation is presented in parentheses.

Billet Assessment

The following parameters were measured on each billet prior to processing:

- Large end diameter under bark or *LEDUB* (m)—measured from the circumference with a diameter tape;
- Small end diameter under bark or *SEDUB* (m)—measured from the circumference with a diameter tape;
- Sweep or *S* (m)—measured as the maximum deviation from a straight edge that bridges the ends of the 1.3 m billets; and
- Shortest small end diameter or *SD* (m)—the shortest small end diameter was measured on the *Eucalyptus dunnii* and *Eucalyptus globulus* billets only using a steel rule.

An additional billet diameter was measured after each billet was rounded by the lathe. This process removed the minimum amount of the outer log required to prepare the billet for rotary peeling and veneer collection. The rounded diameter (*RD*) was measured from the circumference with a diameter tape.

From the measured data, the following parameters were derived for each billet,

$$V = \left(\frac{SEDUB + LEDUB}{2} \right)^2 \times \frac{\pi}{4} \times L \quad (1)$$

where *V* is the individual green billet volume (m³), *SEDUB* and *LEDUB* are described above, π is 3.141593, and *L* is 1.3 m, the nominal length of the billet.

$$D_{CALC1} = SEDUB - S \quad (2)$$

In Eq. 2, *D_{CALC1}* is the geometrically calculated rounded billet diameter (m) that remains once the billet has been rounded to a cylinder in preparation for peeling, and *SEDUB* and *S* are as described above,

$$D_{CALC2} = SD - S \quad (3)$$

with *D_{CALC2}* equal to the geometrically calculated rounded billet diameter (m) that remains once the billet has been rounded to a cylinder in preparation for peeling, and where *SD* and *S* are as described above.

The methodology for calculating the rounded billet diameter based on simple geometrical considerations was developed to investigate its use as a straightforward predictive tool. The calculation was based on two easy-to-measure billet attributes; *SEDUB* and *S*. For *Eucalyptus dunnii* and *Eucalyptus globulus* billets, analysis using *SD* and *S* was also explored to investigate whether the correlation between actual and calculated rounded diameter could be improved with another easily measured log trait.

Billet Processing

Peeling was performed using an OMECO TR4 spindleless veneer lathe. The lathe has backup rollers with ganged teeth which are positioned by a combination of a mechanical and a hydraulic system. A mechanical drive system on the backup rollers turns the billet on the periphery, eliminating the need for traditional spindle mechanisms. The nose bar is a non-driven roller system. The lathe is capable of processing billets with a maximum length of 1,350 mm and maximum log diameter of 400 mm. The minimum peeler core size is 45 mm. The actual peeler core was measured on each billet. A small number of *Eucalyptus nitens* billets were too large (>400 mm) to process on the spindleless lathe. These were rounded and/or partially peeled using a conventional spindled lathe before the peeling was completed on the OMECO TR4 spindleless lathe. For the study, the nominal dried veneer thicknesses were 2.4 mm, 2.5 mm, and 3.0 mm. These were selected to represent the most common veneer thicknesses used for structural veneer-based products in Australia. The lathe was set and operated with best practice operations to provide optimum veneer quality. The majority of billets were preheated until the billet core reached an average of 75 °C using saturated steam prior to peeling.

Veneer Management

The resulting veneer ribbon had green veneer measurements collected and then sequentially clipped to sheets with a 1,400 mm maximum width. This target sheet size was chosen to provide 1,200 mm dried and trimmed veneer sheets as per standard industry practice. Veneers down to 300 mm wide were included, with the exception of a number of 150 mm wide sheets specifically targeted for veneer property evaluations (details not reported). While these 150 mm sheets were not specifically graded, a grade was assigned based on known neighbouring veneer qualities. Veneer sheets were labelled with a unique identifier and seasoned with a conventional jet box veneer drying system using standard commercial practises (temperatures ranged from 160 °C to 190 °C during drying) with a target moisture content of 5%. Veneers were then stabilised to 10% moisture content in storage.

The following parameters were measured on the veneer sheets:

- Green veneer thickness (*GT*)—the thickness of each green veneer sheet, measured using a dial thickness gauge (± 0.01 mm) at three locations along the sheet length;
- Green width (*GW*)—the width (perpendicular to grain) was measured from green veneer sheets prior to clipping and excluded any major defects (*i.e.*, wane or undersize thickness) that was present at the beginning or end of the veneer ribbon;
- Dried veneer thickness (*DT*)—the thickness of each dried veneer sheet, measured using a dial thickness gauge at three locations along the sheet length; and
- Dried veneer width (*DW*)—the width (perpendicular to grain) of each dried veneer sheet.

Visual Grading

Veneer quality was assessed by visual grading in accordance with Australian and New Zealand Standard *AS/NZS 2269.0:2012* (Standards Australia 2012). This standard is widely adopted across the Australian veneer industry and follows the same principles as other international veneer visual grading classification systems. The standard separates structural veneer into four veneer surface qualities and a reject grade according to severity and concentration of imperfections and defects. The grading process was undertaken by a minimum of two experienced graders to minimise variation with defect definition and measurement and to ensure consistent assessment.

Recovery

Four recovery calculation methods were used, including green veneer recovery, gross veneer recovery, net veneer recovery, and graded veneer recovery. Green veneer recovery provides a useful measure of the maximum recovery, taking into account log geometry (sweep, taper, circularity) and lathe limitations (*e.g.*, peeler core size). Green veneer recovery disregards internal log quality. Green veneer recovery (*GNR* as %) was calculated as follows,

$$GNR = \left(\frac{L \times \sum_{\text{veneer}} (GT_{\text{mean}} \times GW)}{\sum_{\text{billet}} V} \right) \times 100 \quad (4)$$

where GT_{mean} is the average green veneer thickness (m) from all measurements taken from the individual trial, GW is the green veneer width (m, perpendicular to grain) as measured prior to clipping and excluding any major defects (*i.e.*, wane or undersize thickness) that were present at the beginning or end of the veneer ribbon, and L and V are as described for Eq. 1.

Gross veneer recovery provides a useful measure of the maximum recovery of dried veneer that meets the quality specifications of *AS/NZS 2269.0:2012* (A-grade to D-grade). This recovery includes the losses accounted for in green veneer recovery but also includes additional losses from visual grading (*i.e.*, veneer which failed to meet grade) and the drying process (*e.g.*, veneer shrinkage, splits, *etc.*). Gross veneer recovery (GSR as %) was calculated as follows,

$$GSR = \frac{L \times \sum_{\text{veneer}} (DT_{mean} \times GRW)}{\sum_{\text{billet}} V} \times 100 \quad (5)$$

where DT_{mean} is the mean dry veneer thickness (m) from all measurements taken from the individual trial, GRW is the width (m, perpendicular to grain) of dried veneer that meets the grade requirements of A, B, C, and D grades in accordance with *AS/NZS 2269.0:2012*, and L and V are as described for Eq. 1.

Net veneer recovery provides a useful measure of process efficiency, as it identifies the saleable product, taking into account the product manufacturing limitations. Net veneer recovery includes the losses accounted for in gross veneer recovery but also includes the additional losses due to the trimming of veneer before, during, and after product manufacture. The loss incurred when veneer sheets are reduced in width to the final product size is known as a trimming factor. In this study the trimming factor was 0.96, which corresponds to reducing the veneer sheet width perpendicular to the grain from 1,250 mm to 1,200 mm. The veneer sheet parallel to the grain was systematically reduced from 1,300 mm to 1,200 mm. Net veneer recovery (NR as %) was calculated as follows:

$$NR = GSR \times 0.96 \times \frac{1200}{1300}$$

$$\text{thus } NR = GSR \times 0.88615 \quad (6)$$

Graded veneer recovery is the net veneer recovery for each grade as defined by *AS/NZS2269.0:2012* (*i.e.*, A, B, C, or D grades). Graded veneer recovery was calculated for each grade quality and is defined as NR_A , NR_B , NR_C , and NR_D .

Statistical Analysis

Analysis of variance and correlation coefficients were calculated to determine associations between the measured traits using IBM SPSS version 21. Pearson's product-moment correlation coefficients were calculated to determine associations between the measured traits. A single factor general linear model was fitted to the untransformed raw data for key variables to assess the difference between species (factors) based on all their billet's variables. *Post hoc* multiple comparison tests were performed through Tukey's Honestly Significant Difference Test. It uses the studentized range statistic to make all

pairwise comparisons between groups and sets the experiment error rate to the error rate for the collection for all pairwise comparisons.

RESULTS AND DISCUSSION

A total of 918 billets from six different hardwood species totalling 48 m³ were processed into rotary veneer. Table 2 provides details of the billet characteristics for each species.

Table 2. Billet Characteristics of the Six Hardwood Species

Species	Average Billet Small-end Diameter Under Bark (cm)	Average Billet Volume (m ³)	Total Volume Processed (m ³)	Average Sweep * (mm)
<i>Corymbia citriodora</i> subsp. <i>variegata</i>	15.6 (2.52)	0.028 (0.009)	5.936	11 (5.09)
<i>Eucalyptus cloeziana</i>	23.5 (5.23)	0.062 (0.027)	13.884	12 (6.98)
<i>Eucalyptus dunnii</i>	17.5 (3.31)	0.035 (0.014)	5.165	10 (5.20)
<i>Eucalyptus pellita</i>	20.9 (3.84)	0.049 (0.019)	6.354	11 (4.77)
<i>Eucalyptus nitens</i>	28.9 (7.09)	0.095 (0.052)	7.778	8 (4.33)
<i>Eucalyptus globulus</i>	25.7 (3.47)	0.072 (0.020)	8.659	11 (5.22)
* Rounded to nearest mm, standard deviation presented in parentheses				

The *Eucalyptus nitens* billets were sourced from the oldest plantations included in this study. *Eucalyptus nitens* billets had the largest average SEDUB and largest average billet volume of 28.9 cm and 0.095 m³, respectively, but also displayed the largest variation ranging from 17.5 cm to 52.0 cm and 0.033 m³ to 0.287 m³, respectively. *Eucalyptus cloeziana* and *Eucalyptus globulus* billets had similar SEDUB characteristics, with averages of 23.5 cm and 25.7 cm, respectively. *Eucalyptus pellita* and *Eucalyptus dunnii* followed with an average SEDUB of 20.9 cm and 17.5 cm, respectively. *Corymbia citriodora* subsp. *variegata* displayed the lowest average SEDUB of 15.6 cm, and, as expected, the lowest average billet volume of 0.028 m³. This species also displayed the least variation in SEDUB and billet volume, ranging from 9.5 cm to 22.5 cm and 0.01 m³ and 0.06 m³, respectively.

The analysis of variance performed on sweep by species showed significant differences between samples of these species. Table 3 displays homogeneous subsets for range tests from *post hoc* multiple comparison tests based on Tukey's Honestly Significant Difference Test. Most of the species exhibited similar billet sweep characteristics (average sweep between 10 and 12 mm), with the exception of *Eucalyptus nitens*, which displayed a significantly lower average billet sweep of 8 mm. This result suggests that, compared to the other species, *Eucalyptus nitens* has a natural tendency toward straightness.

Table 3. Sweep *Post Hoc* Multiple Comparison Tests based on Tukey's Honestly Significant Difference Test

Species	N	Subset		
		1	2	3
<i>Eucalyptus nitens</i>	70	7.6		
<i>Eucalyptus dunnii</i>	146		10.0	
<i>Eucalyptus pellita</i>	129		10.9	10.9
<i>Eucalyptus globulus</i>	120		11.0	11.0
<i>Corymbia citriodora</i> subsp <i>variegata</i>	213		11.4	11.4
<i>Eucalyptus cloeziana</i>	141			12.2
Means for groups in homogeneous subsets are displayed based on observed means. Alpha= 0.05.				

The green veneer recovery depends on the processing cutting pattern. The first step when peeling is rounding, the process whereby the billet is machined to a cylinder with consistent diameter and parallel sides. During this step, no usable veneer is recovered. Thus, in the peeling process, the green recovery depends on the ratio of volumes between a hollow cylinder (rounded billet excluding the peeler core) and an irregular truncated cone (billet). As a consequence, the parameters that impact the rounded billet size and therefore green recovery are primarily SEDUB, sweep, taper, and circularity.

Using billet SEDUB and sweep measurements to predict the billet rounded diameter (calculation method 1 or D_{CALC1}) has proven to be a relevant method with a strong correlation with r^2 values ranging between species from 0.86 to 0.98 when compared with the actual measured rounded billet diameter (Table 4).

Table 4. Coefficients of Determination between Calculated and Actual Measured Rounded Billet Diameter

Species	Calculation Method 1 (r^2)	Calculation Method 2 (r^2)
<i>Corymbia citriodora</i> subsp. <i>variegata</i>	0.93	-
<i>Eucalyptus cloeziana</i>	0.89	-
<i>Eucalyptus dunnii</i>	0.86	0.90
<i>Eucalyptus pellita</i>	0.95	-
<i>Eucalyptus nitens</i>	0.98	-
<i>Eucalyptus globulus</i>	0.87	0.91

Using the billet's shortest diameter (SD) instead of SEDUB, and sweep (calculation method 2 or D_{CALC2}) further improved the correlation for the two species that exhibited the lowest correlation using the first method. This improvement on the coefficient of determination was only 0.04 for both *Eucalyptus dunnii* and *Eucalyptus globulus*. Other factors such as billet surface irregularities (*e.g.*, flutes), which are also more difficult to measure, would only be expected to provide marginal improvements. With coefficient of determination at about 0.9, the unexplained variance is probably mostly due to the experimental measurement error. This indicates that while the second method does provide an improved prediction, either method could be used to predict the effect of billet form on green recovery. This has a range of potential applications

including determining optimal billet grade thresholds and predicting the impact of changing billet length (e.g., 1.3 m versus 2.6 m long billets).

The measured veneer recoveries are displayed in Table 5. All species achieved green veneer recoveries between 68% and 77%. *Eucalyptus globulus* achieved the highest green veneer recovery, while *Corymbia citriodora* subsp. *variegata* achieved the lowest. *Eucalyptus nitens*, *Eucalyptus pellita*, and *Eucalyptus cloeziana* each achieved recoveries within a close range (75% to 73%). *Eucalyptus dunnii* had a recovery (70%) between this group and *Corymbia citriodora* subsp. *variegata*.

Table 5. Veneer Recoveries

Species	Green Recovery (GNR as %)	Gross Recovery (GSR as %)	Gross Recovery Percentage of Green Recovery (%)	Net Recovery (NR as %)
<i>Corymbia citriodora</i> subsp. <i>variegata</i>	68	54	81	48
<i>Eucalyptus cloeziana</i>	73	65	88	58
<i>Eucalyptus dunnii</i>	70	62	89	55
<i>Eucalyptus pellita</i>	74	62	83	55
<i>Eucalyptus nitens</i>	75	62	84	55
<i>Eucalyptus globulus</i>	77	57	75	50

There was a strong correlation ($r^2 = 0.796$, $n = 6$) between species average SEDUB and green veneer recovery. This is understandable since SEDUB has been demonstrated to have a major influence governing the billet rounded diameter and therefore green veneer recovery. This was also observed by Thomas *et al.* (2009) in a study processing plantation eucalypt species within commercial facilities. The relationships that they determined were not as strong as those observed in the current study; however the recovery calculation methodology is not well-explained and may account for the weaker result.

Eucalyptus cloeziana yielded the highest gross and net veneer recoveries of 65% and 58%, respectively, followed by *Eucalyptus dunnii*, *Eucalyptus pellita*, and *Eucalyptus nitens*, which each produced gross and net recoveries of 62% and 55%, respectively. *Eucalyptus globulus* achieved 57% and 50%, respectively, while *Corymbia citriodora* subsp. *variegata* recorded the lowest gross and net recoveries (54% and 48%, respectively). Thomas *et al.* (2009) reported green off-lathe recoveries, which while not clearly defined, are assumed to be similar to gross veneer recovery, typically ranging from 35% to 45% for plantation *Eucalyptus dunnii* aged between 12 and 34 years. Similar recovery values are reported by Blakemore *et al.* (2010) for a small veneering trial processing 21-year-old *Eucalyptus nitens*. These values are quite low compared with this study, which could possibly be attributed to the application of traditional technologies, which produce larger diameter peeler cores and failed peeling due to spindle grip problems (e.g., core splitting). In a study using spindleless lathe technology in China, Luo *et al.* (2013) reported an average green veneer recovery (defined similarly to gross veneer recovery in this study) of 44% (ranging from 28% to 51%) for 11 different five-year-old eucalypt clones. The comparatively low green veneer recovery observed is likely attributable to a lower average small-end diameter of the billets (112 mm).

To clearly separate the billet geometry variation between species from the internal billet qualities, the proportion of gross veneer volume recovered from the green volume has been calculated. *Eucalyptus globulus* produced the lowest proportion of gross veneer volume (75.2%), demonstrating that the samples of this species were most affected by defects preventing veneer sheets from being graded D-grade or higher. *Eucalyptus dunnii* was the least affected (88.8%), followed closely by *Eucalyptus cloeziana* (88.0%), then *Eucalyptus pellita* (83.5%), *Eucalyptus nitens* (83.5%), and *Corymbia citriodora* subsp. *variegata* (80.7%).

The analysis of variance performed on the proportion of recovered gross volume from the recovered green volume by species showed significant differences among species. Table 6 displays homogeneous subsets for range tests from *post hoc* multiple comparison tests based on Tukey's Honestly Significant Difference Test. Interestingly, the best and worst species were both traditional pulp species. *Eucalyptus dunnii* veneer did contain a large presence of imperfections, but they did not have a major impact on the recovery of gross veneer. For example, most veneer sheets contained many knots; however they were generally sound, small in size, and scattered, which resulted in minimal impact when graded. Similarly, *Eucalyptus globulus* veneer contained similar kinds of imperfections, although of much higher frequency and size.

Table 6. Percentage of Gross Veneer Recovered from Green Veneer *Post Hoc* Multiple Comparison Tests based on Tukey's Honestly Significant Difference Test

Species	N	Subset (%)			
		1	2	3	4
<i>Eucalyptus globulus</i>	120	75.2			
<i>Corymbia citriodora</i> subsp. <i>variegata</i>	215		80.7		
<i>Eucalyptus pellita</i>	130		82.8		
<i>Eucalyptus nitens</i>	82		83.5	83.5	
<i>Eucalyptus cloeziana</i>	219			88.0	88.0
<i>Eucalyptus dunnii</i>	166				88.8
Means for groups in homogeneous subsets are displayed based on observed means. Alpha= 0.05.					

These reported recoveries are high when compared with traditional sawmilling practices. The green veneer recoveries measured about twice the comparable recoveries for processing similar plantation resources using traditional sawmilling techniques (green-off-saw recovery, GOS). For example, Leggate *et al.* (2000) reported the green-off-saw recovering for solid wood processing (*i.e.*, sawmilling) of six hardwood *Eucalyptus* sp. at six Queensland plantation sites aged between 21 and 41 years as between 32.3% and 42.9%. The researchers also reported net grade recoveries from the same study for flooring type products of between 8% and 19%. This suggests that rotary veneer processing has the potential to recover up to six times the volume of saleable

product from young plantation species when compared with traditional sawmilling techniques.

Across all species, the recoveries were dominated by D-grade veneer (Table 7). While some species did produce a small amount of A-grade veneer, the recoveries were considered insignificant (<1%). *Eucalyptus nitens* produced the highest percentage of B-grade recovery at 5%, which accounted for 9% of the veneer produced for this species. This was followed by *Eucalyptus cloeziana*, which produced a B-grade recovery of 2.8%. The samples of no other species produced any significant recovery of B-grade quality veneer (>1%). All species produced some C-grade veneer, with *Eucalyptus cloeziana* achieving a remarkable 15.7%, which accounted for 27% of the total volume of veneer for this species. The sampled *Corymbia citriodora* subsp. *variegata*, *Eucalyptus pellita*, and *Eucalyptus nitens* also produced in excess of 10% of the recovered volume of veneer as C-grade quality. Ninety-seven percent of *Eucalyptus globulus* veneer was D-grade.

Table 7. Graded Veneer Recoveries

Species	A-grade Recovery (%)	B-grade Recovery (%)	C-grade Recovery (%)	D-grade Recovery (%)
<i>Corymbia citriodora</i> subsp. <i>variegata</i>	0.2 (0.3)	0.5 (1.0)	7.9 (16.4)	39.6 (82.3)
<i>Eucalyptus cloeziana</i>	0.1 (0.2)	2.8 (4.8)	15.7 (27.1)	39.4 (68.0)
<i>Eucalyptus dunnii</i>	0	0	4.2 (7.7)	50.5 (91.9)
<i>Eucalyptus pellita</i>	0	0.8 (1.5)	5.7 (10.4)	48.2 (88.1)
<i>Eucalyptus nitens</i>	0.2 (0.4)	5.0 (9.1)	7.5 (13.7)	42.1 (76.9)
<i>Eucalyptus globulus</i>	0	0.4 (0.9)	1.2 (2.3)	48.8 (96.8)

* Recovered grade veneer as a proportion of net veneer volume is presented in parentheses.

While D-grade is the lowest visual grade quality for structural veneer, the veneers are suitable for face veneers on non-appearance structural panels as well as the core veneers for most appearance and non-appearance structural panels. The low recovery of higher grade veneers (C-grade and better), which are more suitable for face veneers, would make the commercial production of a standard mix of structural panel products challenging when only using a resource of this quality. According to the Engineered Wood Products Association of Australasia (EWPA, www.ewp.asn.au), the Australian rotary veneer industry requires approximately 30% to 40% of their veneer production to be C-grade or better to enable saleable product manufacture. *Eucalyptus cloeziana* is the only species in this target range, with 32% of veneers produced being C-grade or better. This is followed by *Eucalyptus nitens* (23%), *Corymbia citriodora* subsp. *variegata* (18%), *Eucalyptus pellita* (12%), *Eucalyptus dunnii* (8%), and finally *Eucalyptus globulus* (3%). The blending of plantation hardwoods with higher quality veneers from native forest hardwoods or plantation (softwood or higher quality hardwood) resources may produce a more suitable quality mix.

CONCLUSIONS

1. The study demonstrated that processing representative stands of the current Australian hardwood plantation estate using spindleless veneer lathe technology can overcome many of the problems present when using traditional solid wood processing techniques. Green and gross recoveries achieved during the study were between 68% and 77% and 54% and 65%, respectively. These results are on the order of two to six times what is usually achieved from processing similar resources using traditional solid wood processing systems, presenting an opportunity to process plantation logs of younger ages and of lower quality. The observed differences between species reflect the performances of the plantation resource currently available. These results confound inherent differences between species with silviculture and age effects. Alternative forest management strategies with a focus on veneer products would be expected to improve their performances.
2. The graded veneer recovery was dominated by D-grade veneer across all species. While D-grade is the lowest visual grade quality for structural veneer, the veneers are suitable for face veneers on non-appearance structural panels as well as the core veneers for the vast majority of appearance and non-appearance structural panels. The low recovery of higher grade veneers (C-grade and better) in the studied samples of all species, except possibly *Eucalyptus cloeziana*, would make the commercial production of structural panel products challenging (because of insufficient quantities of face veneer) if a processor were relying solely on this grade of resource. However, the blending of plantation hardwood veneer with higher appearance grade veneer may produce a suitable mix for a range of solid wood end products.
3. Predicting the billet's rounded diameter using easy-to-measure billet form characteristics (small-end diameter under bark or shortest small-end diameter and sweep) was demonstrated to be a satisfactory tool with a coefficient of determination between 0.86 and 0.98. This indicates that this approach could be used to predict the effect of billet form on green recovery and has a range of potential applications, including determining optimal billet grade thresholds and predicting the impact of changing billet length (*e.g.*, 1.3 m versus 2.6 m billets).

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Variation in Rotary Veneer Recovery from Australian Plantation *Eucalyptus globulus* and *Eucalyptus nitens*

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The processing of Australian plantation-grown *Eucalyptus globulus* and *E. nitens* into rotary veneer was shown to produce acceptable recoveries. Three plantation sites for each species were sampled. Silvicultural treatments (thinning and pruning) and growing environments varied between sites. Graded veneer recoveries were dominated by D-grade veneer across all six sites. Variation between the *E. nitens* sites was evident, with recoveries differing between sites reflecting silvicultural treatments. However, only minimal variation in recovery was shown between the *E. globulus* sites. The presence of similar levels of defects across all *E. globulus* sites indicates that the intensive silvicultural management at one site studied was not effective in the production of clear wood, and may possibly have adversely affected grade recovery. Veneer value analysis demonstrated only minimal differences between *E. globulus* sites. More variation was observed in the *E. nitens* value analysis; however, intensive silvicultural management implemented did not necessarily result in higher veneer value.

Keywords: *Eucalyptus*; Veneer; Hardwood; Plantation; Processing; Grade quality; Recovery; Silviculture; Pruning; Thinning

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INTRODUCTION

The establishment of commercial hardwood plantation forests in Australia has seen rapid expansion in recent decades. Gavran (2013) reported that over two million hectares of plantation forestry now exists in Australia, of which about one million are hardwood species. While the industry's softwood sector in Australia has become well-established with reliance on a plantation resource, the hardwood sector remains largely dependent on native forests for log supply, especially for value-added products, including sawn timber and engineered wood products. With increasing limitations preventing access to some native forest areas, as well as the increasing availability of maturing hardwood plantations, interest exists from the processing sector as to the quality and suitability of plantation wood for value-added products. In addition, plantation growers are continuously seeking the processing streams and end uses that can provide the highest return from their plantations.

Of the one million-hectare hardwood estate, *Eucalyptus globulus* and *E. nitens* dominate (55% and 24%, respectively), with over three quarters of the plantation estate

growing these two species (Gavran 2013). Small areas of some plantations have been established and managed with a high-value product focus. Wood *et al.* (2009) reported approximately 26,000 hectares of plantations principally located in Tasmania, which are predominantly *E. nitens* plantations that have been thinned, pruned, and managed for higher-value end-uses. The majority of the estate, however, has been managed for pulpwood markets and is dominated by trees selected primarily by pulpwood properties, and which are therefore mostly unthinned and unpruned. The result is a plantation estate that contains forest and wood qualities that are most likely not optimal for higher-value products. Understanding the quality and variability of the new resource is critical for the wood processing sector's ability to adapt and plan for the future.

Despite the original plantation establishment and management intent, less than favourable market conditions for Australian hardwood pulpwood have prompted the exploration of alternative higher-value markets. As reported by McGavin *et al.* (2014a), the processing of Australian-grown hardwood plantations into veneer using relatively new spindleless veneer lathe technology has the potential to produce veneer recoveries that are more favourable when compared with solid wood processing techniques.

While the veneer recoveries reported by McGavin *et al.* (2014a) were high, the grade recoveries were dominated by D-grade veneers when graded to Australian and New Zealand Standard AS/NZS 2269.0:2012 (Standards Australia 2012). The low recovery of higher-grade veneers (C-grade and better) was identified by McGavin *et al.* (2014a, b) as a challenge for commercial panel production with insufficient proportions of face veneer qualities to allow a standard commercial mix of structural panel products to be manufactured when using only a resource of this quality.

Defects such as bark and decay, encased knots, gum pockets, veneer splits, veneer roughness, and veneer compression were reported by McGavin *et al.* (2014b) as the main contributing defects that cause high proportions of *E. globulus* and *E. nitens* veneer to be restricted to D-grade, the lowest grade described within AS/NZS 2269.0:2012 (Standards Australia 2012).

The analyses reported by McGavin *et al.* (2014a, b) were performed on semi-commercial batches and reported at the species level to provide an overview of the performance of plantation estate eucalypt species. The two species examined in these studies have been previously shown to be genetically stable in different environments (Callister *et al.* 2011; Blackburn *et al.* 2014). Strong race stability and inter-site additive genetic correlations for additive effects in the traits examined were also high, indicating a lack of genotype x environmental interaction at the family level. The overall findings suggest that any significant variation in growth (and therefore associated veneer grade quality traits such as splitting and compression) can mainly be attributed to the stand's silvicultural management and the growing environment in that rotation period.

The objective of this study was to analyse the variation in veneer recoveries, including the defect assessment of veneer produced from a range of mid-rotation *E. globulus* and *E. nitens* plantations. The selected plantations under study represent a range of site qualities and management regimes (*e.g.*, thinning and pruning). The resulting analysis will contribute to the understanding of the quality and variability of the current *E. globulus* and *E. nitens* plantation resources, as well as offer guidance on future plantation management strategies.

EXPERIMENTAL

Plantation Sampling

Plantation trees were sourced from a total of six different sites (three sites for each species), representing a range of site qualities and management regimes (Table 1). The *E. globulus* plantations were located at Deans Marsh, Orford, and Mumbannar in Victoria, while the *E. nitens* plantations were located at Strathblane, Geeveston, and Florentine in Tasmania. Selected trees were representative of diameter at breast height over bark (DBHOB) and form of the surrounding plantation trees most likely to be suitable for veneer or solid wood processing (Table 2). From each selected tree, two 2-m logs were removed from between 0.5 m to 2.5 m and 3.7 m to 5.7 m. Each log was docked to 1.3 m immediately before peeling. The merchandising and docking strategy adopted aimed to simulate the common commercial practice of minimising the time between final billet docking and veneer processing. This is achieved in the industry by maintaining long log lengths after harvesting and only merchandising into billets immediately before processing. The 2 m log sections provided sufficient additional length which was sacrificed to allow the 1.3 m billets to be docked immediately before processing. This removed any degrade from the ends that resulted from the delay between harvesting and veneer processing.

Table 1. Plantation Management History

Species	Plantation Location	Planting Year	Establishment at Stocking (Stems per Hectare)*	Age at Thinning (Years)*	Age at Pruning (Years)**
<i>Eucalyptus globulus</i>	Deans Marsh, Victoria (38°39'S, 143°92'E)	1997	1000	4 and 10 (250 and 190)	4 and 6 (4.5 and 6.5)
<i>Eucalyptus globulus</i>	Orford, Victoria (38°21'S, 142°07'E)	2000	1190	No thinning	No pruning
<i>Eucalyptus globulus</i>	Mumbannar, Victoria (37°96'S, 141°22'E)	2000	1000	No thinning	No pruning
<i>Eucalyptus nitens</i>	Strathblane, Tasmania (43°38'S, 146°94'E)	1993	1250	11 (314)	3 to 4 and 5 (2.5 and 4.5)
<i>Eucalyptus nitens</i>	Geeveston, Tasmania (43°15'S, 146°84'E)	1991	1333	10 (192)	4 to 6 (up to 6.4)
<i>Eucalyptus nitens</i>	Florentine, Tasmania (42°66'S, 146°47'E)	1993	1250	No thinning	No pruning
* Retained stocking (stems per hectare) presented in parentheses					
** Pruned height (metres) presented in parentheses					

Table 2. Plantation Trial Material

Species	Plantation Location	Age (Years)	Number of Trees	Average DBHOB of Plantation Trees * (cm)	Average DBHOB of Selected Trees * (cm)	Thinned and Pruned
<i>Eucalyptus globulus</i>	Deans Marsh, Victoria	16	20	37.0 (4.9)	33.8 (2.6)	Yes
<i>Eucalyptus globulus</i>	Orford, Victoria	13	20	22.2 (5.7)	29.5 (3.2)	No
<i>Eucalyptus globulus</i>	Mumbannar, Victoria	13	20	21.0 (9.8)	28.5 (2.9)	No
<i>Eucalyptus nitens</i>	Strathblane, Tasmania	20	20	31.3 (6.0)	30.0 (3.4)	Yes
<i>Eucalyptus nitens</i>	Geeveston, Tasmania	22	10	43.1 (10.7)	42.0 (9.8)	Yes
<i>Eucalyptus nitens</i>	Florentine, Tasmania	20	11	26.9 (11.1)	33.8 (2.6)	No
* Standard deviation presented in parentheses						

Billet Assessment

The following parameters were measured on each billet prior to processing:

- Large end diameter under bark, *LEDUB* (m)—measured from the circumference with a diameter tape;
- Small end diameter under bark, *SEDUB* (m)—measured from the circumference with a diameter tape; and
- Sweep, *S* (m)—measured as the maximum deviation from a straight edge that bridges the ends of the 1.3-m billets.

From the measured data, billet volumes were derived following the methodology adopted by McGavin *et al.* (2014a).

Billet Processing

Processing was undertaken using an OMECO spindleless veneer lathe, model TR4 (OMECO, Curitiba, Estado de Paraná, Brazil). The lathe is capable of processing billets with a maximum length of 1350 mm and a maximum log diameter of 400 mm. The minimum peeler core size was 45 mm. Twelve *E. nitens* billets from the Geeveston site, which were too large (> 400-mm diameter) to directly process on the spindleless lathe were rounded and/or partially peeled using a conventional spindled lathe before the peeling was completed on the spindleless lathe. For the study, the lathe settings and log conditioning were fixed, and the nominal dried veneer thickness was 2.5 mm.

The resulting veneer ribbon was sequentially clipped to target 1400-mm maximum width sheets. This target sheet size was chosen to provide 1200-mm dried and trimmed veneer sheets as per standard industry practise. Veneer widths as narrow as 300 mm were included, while veneer sheets narrower than 300 mm were discarded. Veneer sheets were labelled with a unique identifier. Clipped veneer was seasoned using a conventional jet box veneer drying system using standard commercial practises (temperatures ranged from 160 to 190 °C during drying), with a target moisture content of 5%. Veneers were then stabilised to 10% moisture content in storage.

A more detailed description of the methodology regarding billet preparations and processing is described by McGavin *et al.* (2014a).

Visual Grading

Veneer quality was assessed by visual grading in accordance with Australian and New Zealand standard AS/NZS 2269.0:2012 (Standards Australia 2012). This standard is widely adopted across the Australian veneer industry and follows the same principles as other international visual grading classification systems. The standard separates structural veneer into four veneer surface qualities and a reject grade according to the severity and concentration of imperfections and defects.

To facilitate comparisons between species and sites, only resource-related defects have been included in this analysis. Defects that could be directly attributed to the veneering process, such as splitting caused by veneer handling, have been excluded from the analysis so as to not disadvantage any particular species or site that may benefit from a further refined process. For each veneer, the visual grade was recorded for each type of defect present within the veneer. This allowed the analysis of the impact of each type of defect in terms of its contribution to the assigned grade of each veneer. The defects that caused the lowest visual grade were identified as grade-limiting defects, and the resulting assigned grade was recorded for each veneer. The grading process was undertaken by a minimum of two experienced graders to minimise variation with defect definition and measurement, as well as to ensure consistent assessment.

Recovery

Four recovery calculations following the same methodology as detailed by McGavin *et al.* (2014a) were made to determine green veneer recovery, gross veneer recovery, net veneer recovery, and graded veneer recovery.

Green veneer recovery was calculated using average green veneer thickness; green veneer width (perpendicular to grain) as measured prior to clipping and excluded any major defects (*i.e.*, wane or undersize thickness) that were present at the beginning or end of the veneer ribbon; veneer length (same as billet length); and billet volume.

Gross veneer recovery was calculated using average dry veneer thickness; veneer width (perpendicular to grain) of dried veneer that met the grade requirements of A-grade, B-grade, C-grade, and D-grade in accordance with AS/NZS 2269.0:2012; veneer length (same as billet length); and billet volume.

Net veneer recovery was calculated as the gross veneer recovery minus a trimming factor. Graded veneer recovery was the net grade recovery separated into individual grades (A-grade, B-grade, C-grade, and D-grade) expressed as a proportion of net recovered volume. Veneers that did not meet these grade requirements were labelled reject grade (F-grade).

Relative Veneer Value

Accurate commercial veneer values for the species included in the study are difficult to determine; however, to provide an indication of the economic impact that the different species and plantation sites had on veneer value, relative values for each grade were provided by the Engineered Wood Products Association of Australasia (2014). This suggests that C-grade veneer attracts a value 1.2 times higher than D-grade, B-grade attracts a value 1.7 times than D-grade, and A-grade attracts a value three times higher

than D-grade. Reject grade is considered of no value. This analysis focuses on the ratios of veneer grades recovered and discounts for the variation in veneer volume recovered.

RESULTS AND DISCUSSION

Visual Grading

A total of 202 billets (16.4 m³) from six different hardwood plantations were processed using a spindleless lathe, which produced 3,097 m² of rotary veneer. Table 3 provides details of the billet characteristics for each site.

Table 3. Billet Characteristics of the Six Hardwood Plantation Sites

Plantation Location	Species	Thinned and Pruned	Average Billet Small-end Diameter under Bark (cm)	Average Billet Volume (m ³)	Total Volume Processed (m ³)	Average Sweep (mm)
Deans Marsh	<i>Eucalyptus globulus</i>	Yes	28.4 (3.2)	0.088 (0.019)	3.517	12 (5.0)
Orford	<i>Eucalyptus globulus</i>	No	24.8 (2.7)	0.067 (0.015)	2.661	10 (5.4)
Mumbannar	<i>Eucalyptus globulus</i>	No	23.8 (2.7)	0.062 (0.015)	2.482	11 (5.3)
Strathblane	<i>Eucalyptus nitens</i>	Yes	24.6 (3.1)	0.067 (0.017)	2.663	8 (4.8)
Geeveston	<i>Eucalyptus nitens</i>	Yes	36.6 (9.2)	0.152 (0.074)	3.039	6 (3.2)
Florentine	<i>Eucalyptus nitens</i>	No	29.6 (2.5)	0.094 (0.017)	2.075	8 (3.9)

Standard deviation presented in parentheses.

The measured veneer recoveries are displayed in Table 4.

Table 4. Veneer Recoveries

Plantation Location	Species	Thinned and Pruned	Green Recovery (%)	Gross Recovery (%)	Gross Recovery Percentage of Green Recovery (%)	Net Recovery (%)
Deans Marsh	<i>Eucalyptus globulus</i>	Yes	77	56	73	49
Orford	<i>Eucalyptus globulus</i>	No	77	58	77	51
Mumbannar	<i>Eucalyptus globulus</i>	No	77	59	77	52
Strathblane	<i>Eucalyptus nitens</i>	Yes	76	64	84	56
Geeveston	<i>Eucalyptus nitens</i>	Yes	74	61	82	54
Florentine	<i>Eucalyptus nitens</i>	No	76	61	79	54

All sites achieved similar green veneer recoveries of between 74% and 77%. The *E. globulus* sites achieved gross recoveries of between 56% and 59%, with Deans Marsh achieving the lowest gross recovery value (56%), despite receiving the most intensive silvicultural management. The *E. nitens* sites achieved higher gross recoveries of between 61% and 64%, with the Strathblane site achieving the highest gross recovery (64%). Geeveston and Florentine both achieved gross recoveries of 61%. The net recoveries are proportional to the gross recovery values.

The recoveries measured in this study are high compared to most previous studies in Australia when rotary peeling eucalypt species. For example, Thomas *et al.* (2009) reported green off-lathe recoveries for plantation *E. dunnii* (aged between 12 and 34 years-old) ranging from 35% to 45%. Blakemore *et al.* (2010) reported similar recovery values for a small-scale *E. nitens* (21-year-old) veneering trial. The difference in recoveries between the previous studies and this study is probably attributed to the application of traditional technologies (spindled lathe), which produce larger diameter peeler cores and failed peeling due to spindle grip problems (*e.g.*, core splitting). Different veneer grading methods also help explain the variation.

Luo *et al.* (2013) reported an average green veneer recovery (defined similarly to gross veneer recovery in this study) of 44% (ranging from 28% to 51%) for 11 different five-year-old eucalypt clones in China. While adopting spindleless lathe technology, similar to this study, the comparatively low green veneer recovery observed is likely attributable to a lower average small-end diameter of the billets (112 mm). The recoveries are comparable to those reported by McGavin *et al.* (2014a) using similar processing technologies and methodologies to this study, for the assessment of six Australian hardwood plantation species.

There was no relationship between billet SEDUB and veneer recovery because of the compounding influences of billet geometry (*i.e.*, sweep, taper, ovality, and surface irregularities) and billet end splitting, as well as billet core defects, which influence the residual peeler core diameter (McGavin *et al.* 2014a).

Table 5 provides details of the grade recovery (recovered veneer for each grade as a proportion of total veneer surface area) for each site.

Table 5. Graded Veneer Recovery (Recovered Veneer for Each Grade as a Proportion of Total Veneer Surface Area)

Plantation Location	Species	Thinned and Pruned	A-grade Recovery (%)	B-grade Recovery (%)	C-grade Recovery (%)	D-grade Recovery (%)	Reject Recovery (%)
Deans Marsh	<i>Eucalyptus globulus</i>	Yes	0.0	1.3	3.4	80.7	14.6
Orford	<i>Eucalyptus globulus</i>	No	0.0	1.1	2.3	86.5	10.1
Mumbannar	<i>Eucalyptus globulus</i>	No	0.0	0.9	2.0	87.1	10.0
Strathblane	<i>Eucalyptus nitens</i>	Yes	1.1	22.9	20.8	52.4	2.8
Geeveston	<i>Eucalyptus nitens</i>	Yes	0.1	7.4	17.1	64.9	10.5
Florentine	<i>Eucalyptus nitens</i>	No	0.0	0.5	4.6	93.1	1.8
* Recovered grade veneer as a proportion of veneer surface area							

Despite the Deans Marsh site having intensive silvicultural management, implemented to increase proportions of higher-quality end-products, there was minimal difference in the spread of veneer grades. The D-grade recovery was less for the Deans Marsh site compared with the two unthinned and unpruned *E. globulus* sites at Orford and Mumbannar; however, the recovery of reject grade was higher, resulting in minimal improvement being observed in higher-grade qualities (C-grade and better). This explains the lower gross recovery observed for Deans Marsh in comparison with the other two sites (Table 4), which had comparable graded veneer recoveries. The spread of grade recoveries are consistent with other similar studies, such as Peng *et al.* (2014), who reported over 80% of eucalypt hybrid veneers being categorised as D-grade (although based on a slightly different grading standard), and less than 3% of veneers meeting the grade requirements of C-grade or better (with the balance being reject grade).

A greater variation was shown in grade recoveries between the three *E. nitens* sites. The Florentine site, which was not thinned or pruned, was almost totally dominated by D-grade veneer (93.1%), and as expected, the thinned and pruned Strathblane and Geeveston sites achieved an improved spread of recoveries across higher-grade qualities when compared with the Florentine site. Of the three *E. nitens* sites, the Strathblane site performed best, with superior recovery of higher grades (C-grade and better). For example, the Strathblane site achieved three times more B-grade veneer than the Geeveston site, despite the latter being thinned and pruned and having the largest diameter billets. The Geeveston site yielded a higher reject recovery (10.5%), which was three to five times higher than the other two *E. nitens* sites (1.8% and 2.8%, respectively).

The Engineered Wood Products Association of Australasia (2013) suggests that the rotary veneer industry requires approximately 30% to 40% of their graded veneer production to be at least C-grade or better to enable saleable product manufacture. The Strathblane site was the only site to achieve this benchmark, with 45% of veneer meeting the grade requirements of C-grade or better.

Table 6 illustrates the five highest-ranked defects (in order of severity) that prevented veneers from attaining grades higher than D-grade for each site.

All six sites were impacted by similar defects. Bark pockets or decay, mostly surrounding knots, was the highest-ranked grade-limiting defect in five of the six sites, and it ranked second in the remaining site. While highly ranked, the impact was more severe for *E. globulus*. The presence of these defects in the peeled veneer supports the findings of previous research studies, which have shown that these species may not heal well after pruning or self-pruning, with the section of stem-wood laid down post-pruning being prone to decay entry and slow occlusion (Wardlaw and Neilson 1999; Pinkard 2002; Pinkard *et al.* 2004; Deflorio *et al.* 2007).

Encased knots also featured heavily across all sites, although they had less impact in the thinned and pruned *E. nitens* sites (Strathblane and Geeveston). Despite the Deans Marsh *E. globulus* site also being thinned and pruned, there was little benefit gained when compared with results from the unthinned and unpruned *E. globulus* sites. Instead of the veneer of the pruned billets being knot-free (at least from the pruned diameter plus an allowance for branch occlusion), the tree seems to have not been effective in producing knot- (and knot-related defects-) free wood; rather, the branch stubs produced a deficient occlusion pattern (along with a high proportion of gum pockets) as the tree grew.

Table 6. Top Five Ranked Defects Preventing Veneers from Attaining Assigned Grades Higher than D-grade

Plantation Location	Species	Thinned and Pruned	Rank				
			1	2	3	4	5
Deans Marsh	<i>Eucalyptus globulus</i>	Yes	Bark or decay (85%)	Gum pockets (64%)	Encased knots (48%)	Roughness (41%)	Compression (35%)
Orford	<i>Eucalyptus globulus</i>	No	Bark or decay (82%)	Gum pockets (68%)	Encased knots (62%)	Roughness (31%)	Compression (26%)
Mumbannar	<i>Eucalyptus globulus</i>	No	Bark or decay (93%)	Encased knots (75%)	Gum pockets (52%)	Roughness (33%)	Compression (25%)
Strathblane	<i>Eucalyptus nitens</i>	Yes	Bark or decay (36%)	Encased knots (24%)	Roughness (8%)	Splits (5%)	Gum pockets (4%)
Geeveston	<i>Eucalyptus nitens</i>	Yes	Bark or decay (43%)	Encased knots (35%)	Splits (30%)	Roughness (12%)	Defect combination (9%)
Florentine	<i>Eucalyptus nitens</i>	No	Encased knots (86%)	Bark or decay (46%)	Splits (22%)	Roughness (17%)	Gum pockets (9%)
Note: The proportion of veneer impacted by each defect is provided in parentheses.							

Gum pockets ranked highly for the *E. globulus* sites. As suggested by McGavin *et al.* (2014b), the size of this defect was often small and concentrated, and while it would influence the appearance of the veneer, it would be expected to have a negligible effect on mechanical properties or on the panel manufacturing process. The characteristics of this defect in the veneer are such that it may be unnecessarily severe to downgrade such quantities of veneer to D-grade, especially when compared with other appearance-affecting defects, which are permissible in higher grades. A market acceptance analysis and review of the permissible limits outlined in the grading standards for this defect could be beneficial.

Veneer surface roughness ranked either third or fourth for preventing veneer from all sites from attaining a grade higher than D-grade. Veneer surface roughness is mostly present in areas of veneer where there is grain deviation present, such as around knots and knot holes. This was supported by the fact that surface roughness has more impact on *E. globulus* veneers, which also reported a higher severity of encased knots when compared with *E. nitens*. McGavin *et al.* (2014b) reported a significant ($p < 0.001$) and positive, although relatively weak correlation between sound or encased knot rank and veneer surface roughness rank.

Splits ranked third for the Geeveston and Florentine *E. nitens* sites. While splits ranked fourth for Strathblane, splits only prevented 5% of veneers from attaining a grade higher than D-grade for this site. Splits fell outside the top five ranked defects (Table 6) for *E. globulus* sites; however, splits were responsible for between 10% and 15% of veneers' inability to attain a grade higher than D-grade.

Compression in the *E. globulus* veneer (ranked fifth) resulted in 25% to 35% of veneer being restricted to D-grade. This defect was much more obvious when the veneer

was dried, with many veneers being “rippled” and uneven. The presence of this defect can be attributed to the differential transverse shrinkage induced by the frequent presence of veins or casts of tension wood within this species (Washusen and Ilic 2001), and it has been shown to cause product recovery losses in sawn timber (Washusen 2011). Compression had less impact on the grade recovery of *E. nitens* veneer.

McGavin *et al.* (2014b) reported a grade scenario based on the improvement of veneer grade made possible with the implementation of effective pruning. For *E. globulus*, the simulated improvement included changes in veneer grade recovery percentage of −9% for D-grade, +11% for C-grade, and +5% for B-grade (difference between measured and simulated). A-grade remained unchanged at 0%. The simulated benefits of pruning were not supported within this study for *E. globulus*, with a negligible difference in grade recovery between the pruned and thinned site and the two unpruned and unthinned sites. The presence of defects, including bark pockets and decay, which were mostly associated with knots, encased knots, surface roughness, and gum pockets in similar proportions across all sites, suggest that at the Deans Marsh site the pruning had not been effective in allowing clear wood to be produced. This may be due to suboptimal pruning techniques, timing and procedures, and/or may be a physiological characteristic of this species (Wardlaw and Neilson 1999; Pinkard 2002; Pinkard *et al.* 2004; O’Hara 2007; Deflorio *et al.* 2007). An additional influence may be the below average rainfall (665 mm in 2004, 709 mm in 2005, and 474 mm in 2006 recorded at the site compared with a 852 mm long-term average) the Deans Marsh site received for the three years following the last pruning. This almost certainly impacted the rate and processing of branch stub occlusion.

The same grade scenario reported by McGavin *et al.* (2014b) simulating effective pruning for *E. nitens* produced a change in grade recovery percentage of −33% for D-grade, +16% for C-grade, and +19% for B-grade grade (difference between measured and simulated). This is close to what was observed in the present study, with D-grade recoveries for both the thinned and pruned sites having between 28% and 41% less than the unthinned and unpruned site, while C-grade recoveries for the thinned and pruned sites were between 13% and 16% higher than the unthinned and unpruned Florentine site. The thinned and pruned Strathblane site had the most favourable result and was comparable to the grade simulation, with 22.5% higher grade recovery for B-grade veneers when compared with the Florentine site. The thinned and pruned Geeveston site produced 7% higher B-grade than the Florentine site. The gains simulated by McGavin *et al.* (2014b) and measured in this study are greater than the grade quality difference reported by Blakemore *et al.* (2010) for a small study that included five pruned and five unpruned *E. nitens* trees. In this study, the changes in percentage recoveries with pruned billets compared with unpruned billets were as follows: A-grade +5.7%; B-grade +3.1%; C-grade +3.8%; D-grade +0.5%; and reject grade −13.1%. It should be noted, however, that the veneer quality from the unpruned trees was already much higher than presented in Table 5, with over 50% of the resulting veneer achieving C-grade or better. Moreover, the trees sampled by Blakemore *et al.* (2010) were bigger (mean diameter of 50.6 cm) than in this study, and the peeling and grading methods were different, making any comparison between the studies speculative.

Across all sites, the major cause for veneer being labelled reject grade was a combination of multiple defects that individually were within permissible limits of higher grades, but when combined in close proximity (*i.e.*, defect combination), prevent veneers from attaining higher grades. For the *E. globulus* sites, the high incidence of a range of

defects, including bark and decay, encased knots, gum pockets, *etc.* contributed to reject recoveries of between 10.0% and 14.6%. For *E. nitens*, the Strathblane and Florentine sites had low reject recoveries (1.8% to 2.8%); however, the heavily thinned and pruned Geeveston site had 10.5% reject recovery. The defect that contributed to this variation was the high occurrence of splits in Geeveston veneers. The Geeveston billets were also observed to have severe splitting prior to peeling, which obviously carried through to the veneer. The presence of these splits is an indicator of high levels of growth stresses, most likely exacerbated by the relatively late and heavy thinning. This may have caused severe destabilisation among the remaining trees and consequently induced high levels of growth stresses. The release of these stresses has been shown to result in severe billet end splitting (Kubler 1988).

Figures 1 through 6 illustrate the distribution of assigned grades for individual grade-limiting defects for each species. In this type of diagram, each bubble represents the percentage of a given grade for a given defect. The grey scaling and diameter of the bubble are both proportional to the percentage of the total veneer surface area for each individual defect. In addition, similarly for each defect, the assigned grade is determined for each veneer from the defect(s) causing the lowest individual grade.

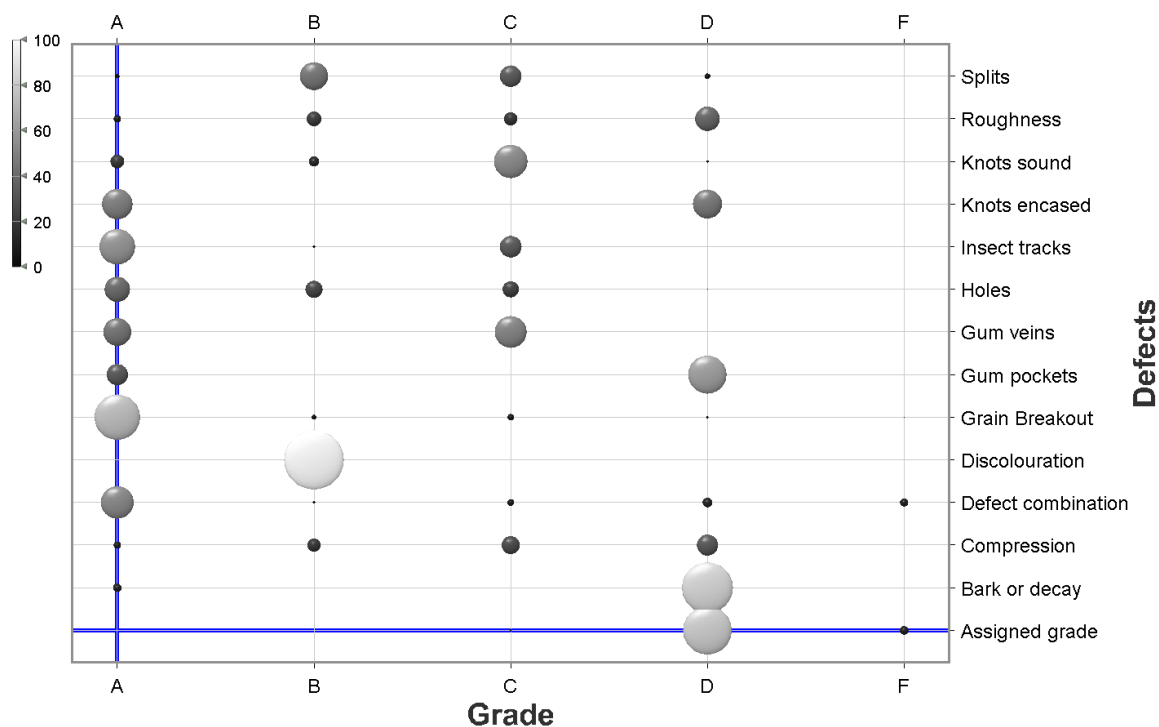


Fig. 1. Distribution of Deans Marsh *Eucalyptus globulus* visually-assigned veneer grades for a range of resource-related defects. Like the grey scale, the size of the bubble is proportional to the recovered value.

From these figures, the distribution of grade-limiting defects within C-grade and higher-grade veneer show some dissimilarities. For *E. globulus*, the most noticeable variation involves the Deans Marsh site, where insect tracks and gum veins have more impact on the reduction of veneer grade compared with the other two *E. globulus* sites at Orford and Mumbannar. This demonstrates the negative impact of pruning followed immediately by drought.

For *E. nitens*, the presence of holes impacted the Florentine site at a much lower grade compared with Strathblane and Geeveston. This is a consequence of dead branch persistence in logs from this unpruned and unthinned site.

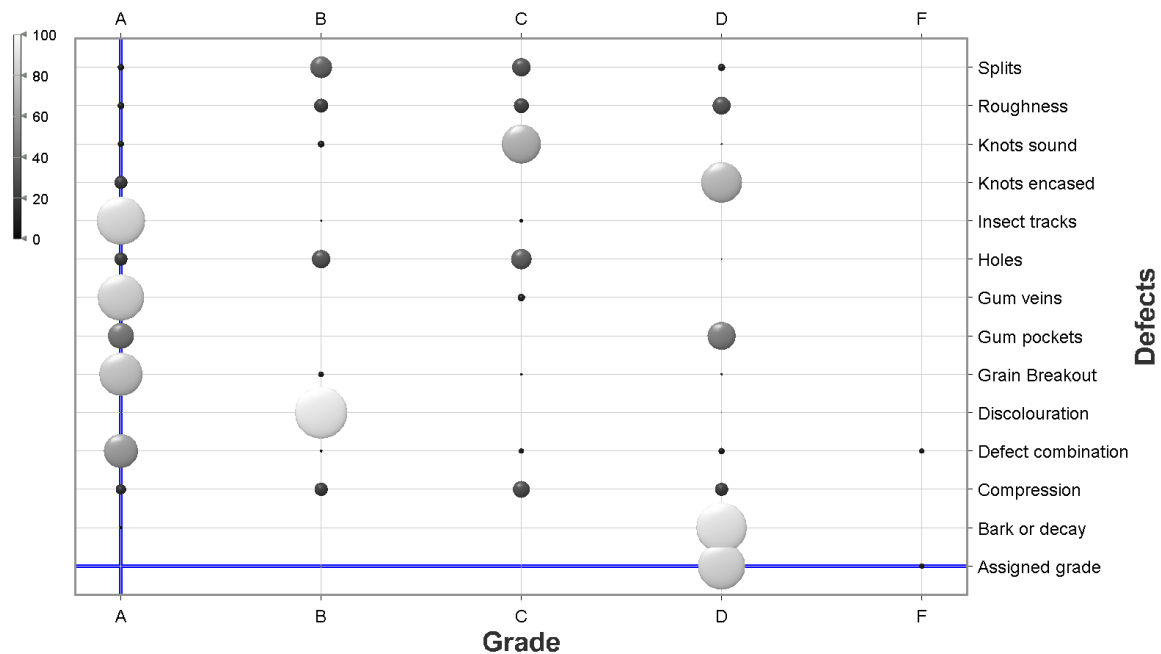


Fig. 2. Distribution of Orford *Eucalyptus globulus* visually-assigned veneer grades for a range of resource-related defects. Like the grey scale, the size of the bubble is proportional to the recovered value.

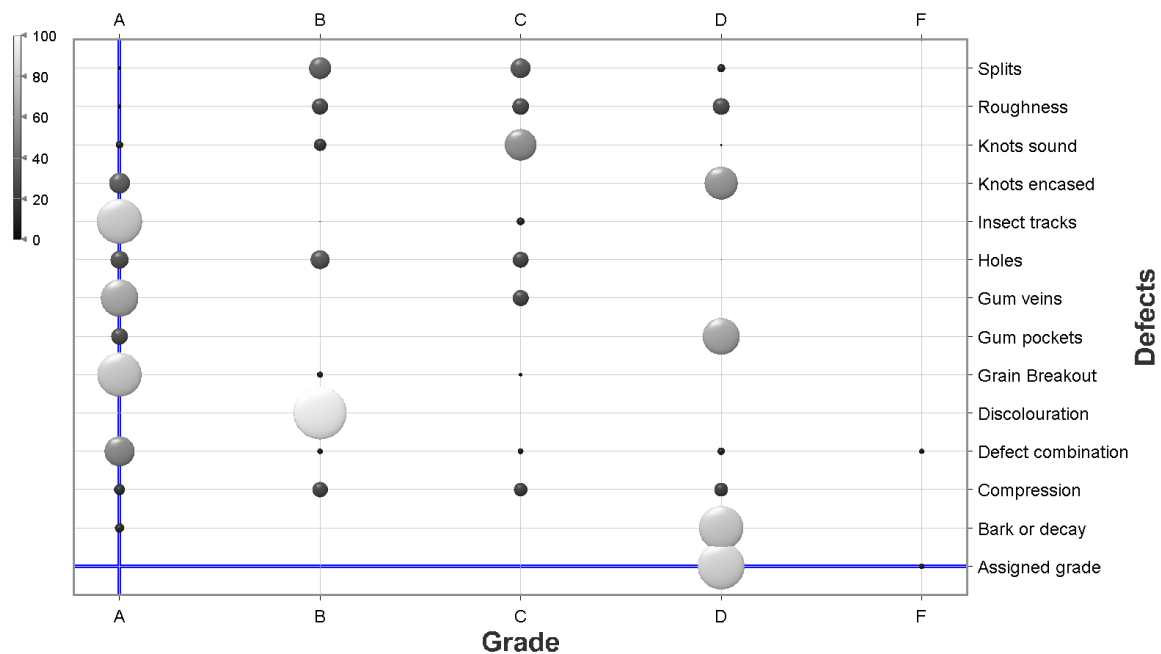


Fig. 3. Distribution of Mumbannar *Eucalyptus globulus* visually-assigned veneer grades for a range of resource-related defects. Like the grey scale, the size of the bubble is proportional to the recovered value.

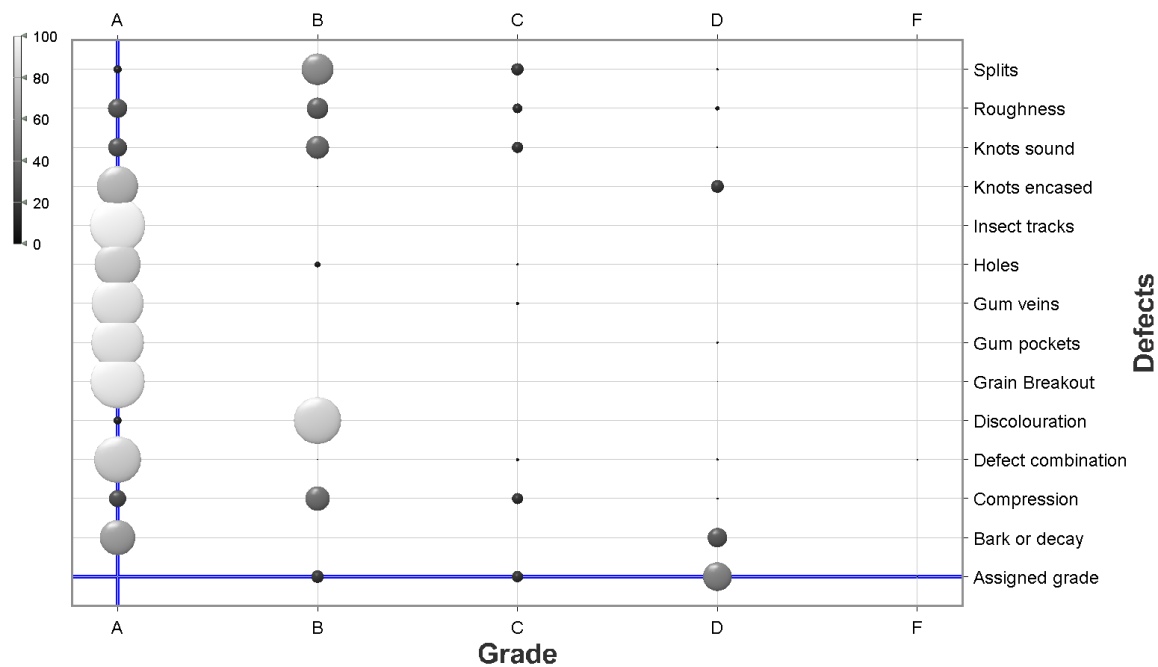


Fig. 4. Distribution of Strathblane *Eucalyptus nitens* visually-assigned veneer grades for a range of resource-related defects. Like the grey scale, the size of the bubble is proportional to the recovered value.

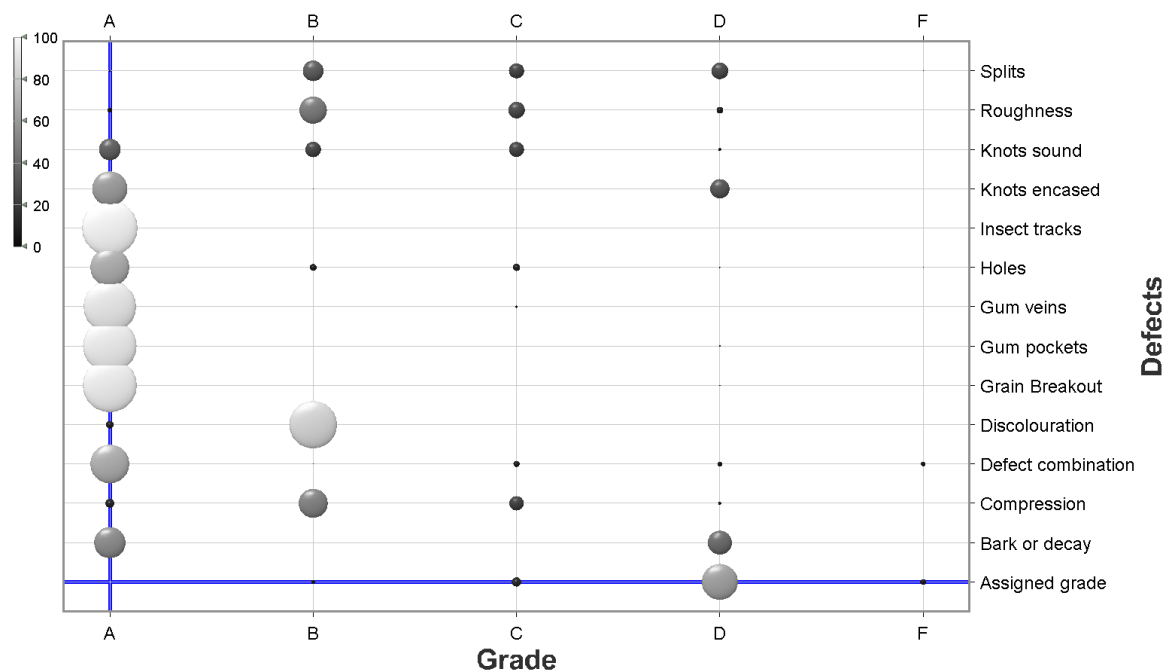


Fig. 5. Distribution of Geeveston *Eucalyptus nitens* visually-assigned veneer grades for a range of resource-related defects. Like the grey scale, the size of the bubble is proportional to the recovered value.

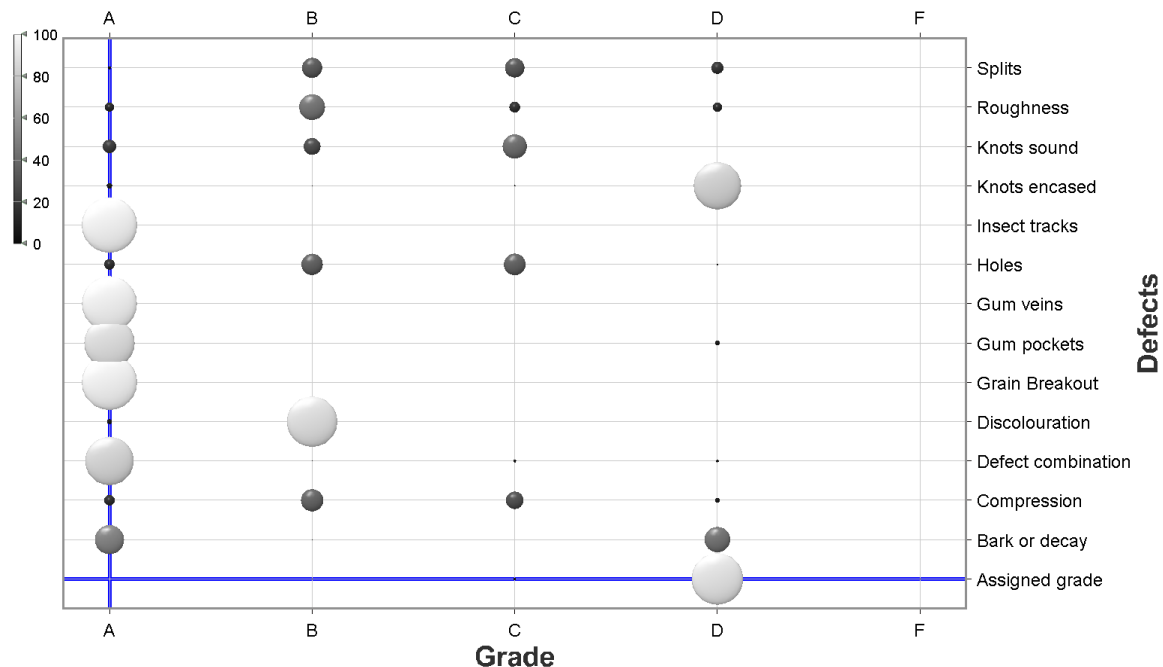


Fig. 6. Distribution of Florentine *Eucalyptus nitens* visually-assigned veneer grades for a range of resource-related defects. Like the grey scale, the size of the bubble is proportional to the recovered value.

Economic Impact

Table 7 displays the relative veneer value as a proportion of the maximum possible value for each site. The analysis acknowledges that the maximum value can only be achieved if the A-grade recovery is 100%.

Table 7. Relative Veneer Value as a Proportion of Maximum Possible Value*

Plantation Location	Species	Thinned and Pruned	Proportion of Maximum Possible Value (%)
Deans Marsh	<i>Eucalyptus globulus</i>	Yes	29.0
Orford	<i>Eucalyptus globulus</i>	No	30.4
Mumbannar	<i>Eucalyptus globulus</i>	No	30.3
Strathblane	<i>Eucalyptus nitens</i>	Yes	39.9
Geeveston	<i>Eucalyptus nitens</i>	Yes	32.8
Florentine	<i>Eucalyptus nitens</i>	No	33.2

*A-grade recovery of 100% is used as a benchmark for the maximum percentage value.

There was minimal variation between the *E. globulus* sites. Deans Marsh veneers, which received the most intensive silvicultural treatment out of the *E. globulus* sites, demonstrated no benefit in terms of veneer grade quality and achieved a slightly lower relative value. The lower value in comparison with the other *E. globulus* sites is a direct result of the higher proportion of reject grade, which attained no value in the analysis.

More variation existed within the *E. nitens* analysis in line with the grade recovery variation. Strathblane proved to be superior, achieving 40% of the maximum possible value. This was greatly assisted by the higher proportion of B-grade by comparison, which attracts a value 1.7 times the value of D-grade. In relative veneer

value, the Strathblane site had a 22% gain over Geeveston, which attained a similar relative veneer value to the Florentine site. While Geeveston achieved much higher proportions of C-grade and better veneers in comparison with the Florentine site, it was not enough to offset the impact of the high proportion of reject grade by comparison, which attained no value in the analysis.

CONCLUSIONS

1. This study demonstrated that plantation *E. globulus* and *E. nitens* can produce acceptable marketable product recoveries of rotary veneer; however, the graded veneer recovery was dominated by D-grade veneer across most sites. The low recovery of higher-grade veneers (C-grade and better), which are more in demand for face veneers, will make the commercial production of a standard mix of saleable structural panel products challenging if relying on this resource alone.
2. Variation between the *E. nitens* sites was evident, with gross, net, and grade recoveries being different between sites that were thinned and pruned and the site that wasn't. The best-performing site (Strathblane) achieved a recovery of C-grade and better veneers by 45%. This exceeds the minimum grade quality proportions nominated by the Engineered Wood Products Association of Australasia (30% to 40%) necessary for the commercial production of structural panel products.
3. Variation in recoveries was less evident between the thinned and pruned *E. globulus* site, as well as between the unthinned and unpruned sites. The presence of defects, including bark pockets and decay, which were mostly associated with knots, encased knots, surface roughness, and gum pockets in similar levels across all sites suggests that while pruning and thinning were conducted within the Deans Marsh site, the pruning had not been effective in allowing clear wood to be produced. This may be because of suboptimal pruning techniques, timing and procedures, physiological characteristics of this species, or drought stress resulting from the below average rainfall for the three years following the last pruning.
4. The difference in grade recovery between the thinned and pruned *E. nitens* sites and the unthinned and unpruned site was in line with the grade simulation reported by McGavin *et al.* (2014b), which describes the improvement of veneer grade by implementing effective pruning. The simulated benefits of pruning were not supported within this study for *E. globulus*, with negligible difference in grade recovery between the pruned and thinned site and the two unpruned and unthinned sites. These results indicate that the grade scenario methodology to simulate the potential grade improvement with effective pruning as proposed by McGavin *et al.* (2014b) could be a valuable tool for use in the economic modelling of silvicultural treatments, at least for *E. nitens*.
5. The veneer value analyses demonstrated minimal difference between the *E. globulus* sites, which is in line with the grade recovery. The higher proportion of reject grade veneers produced by the Deans Marsh site contributed to the slightly lower value in comparison with the other sites, despite this site receiving intensive silvicultural treatments. More variation existed within the *E. nitens* analysis. The Strathblane site proved to be superior, achieving 40% of the maximum possible value. This was

greatly assisted by the higher proportion of B-grade by comparison, which attracts a value 1.7 times the value of D-grade. Like the Strathblane site, Geeveston was also thinned and pruned; however, this site attained a similar relative veneer value to the Florentine site, which received no treatment. While Geeveston achieved much higher proportions of C-grade and better veneers in comparison with the Florentine site, it was not enough to offset the impact of the high proportion of reject grade by comparison, which attained no value in the analysis.

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